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Characteristics of a Linear Actuator for an Automated Manual Transmission (AMT)

Undergraduate Research Thesis

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Abstract

The scope of this research is to design a suitable experiment that will allow to accurately find the parameters of the actuators that control the transmission. The purpose is to find these parameters in order to develop the dynamic model to enable model based control (mbc). An automated manual transmission (AMT) is an innovative type of transmission that combines the advantages of both a manual transmission (MT) and an automatic transmission (AT). The end goal of this research is to use existing actuators that are made by SKF and understand their behavior under extreme operating conditions to ensure their success as part of the AMT. The project also involved designing test stands such that actuators could be tested under identical conditions for each iteration of extension and retraction of the actuating end. These tests are carried out to find the parameters as well as the internal efficiency of the actuator system. The idea is to study the behavior of the actuator over a large number of tests and see the variance in the parameters with respect to changing voltage and load inputs. The efficiency is calculated based on these parameters. Finding the system efficiency helps in calculating internal losses as there is no accurate method for modeling the interaction between the different parts. These findings will be used by The Ohio State University EcoCAR 2 team for designing the control algorithm for the AMT that will be used in the development of a prototype plug-in hybrid vehicle (PHEV) that is based on a 2013 Chevrolet Malibu. This thesis also deals with the black box model of the electro-mechanical clutch actuator. Further work on this project will include the possibility of replacing the existing actuators with quicker and more efficient ones.

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Acknowledgements

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Chapter 1: Introduction

1.1 Background

The world's crude oil reserves have been falling at an alarming rate given the exponential increase in the number of vehicles as well as industries that have been growing over the years in every corner of the planet. This necessitates having to consider using alternate fuels that are sustainable as well as more environmentally friendly.

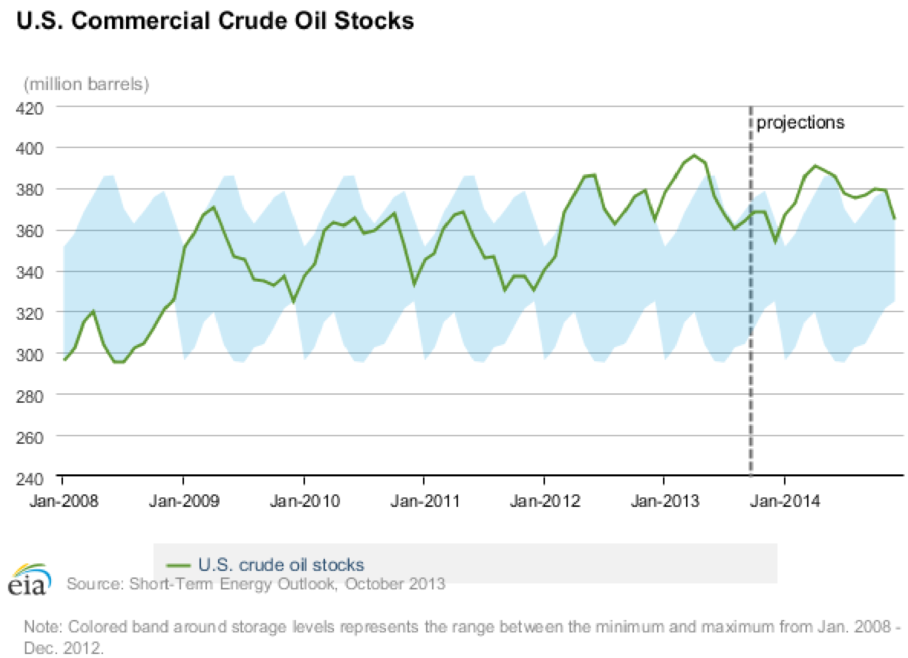

Figure 1: EIA's short term outlook on US crude oil reserves [1]

The automotive industry has been faced with increasingly tighter regulations regarding fuel consumption as well as emissions. This has laid the focus on development of vehicles that have powertrains based on alternate sources of fuel/energy. Out of these, the hybrid powertrain is the most common and has become more popular over the years. While some manufacturers use the concept of "mild hybrids" – which essentially feature a start-stop mechanism whereby the engine can be stopped during standstill and restarted by accelerating which allows for fuel savings, most manufacturers in the past few years have been developing full hybrids.

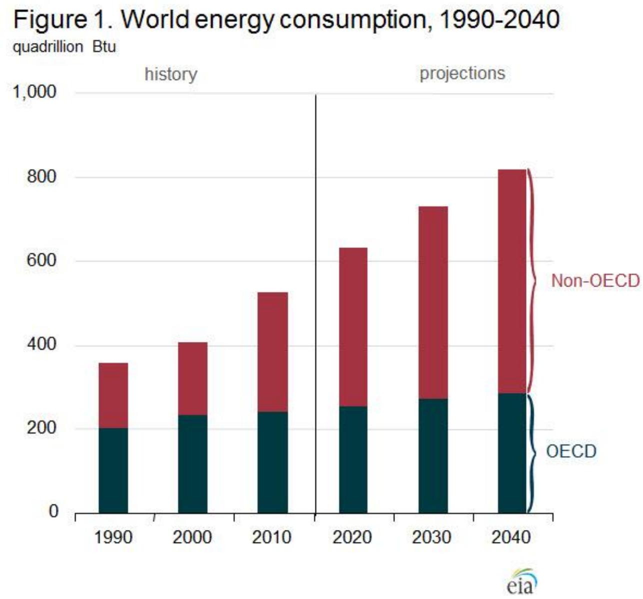

Figure 2: EIA's World Energy Consumption [1]

Hybrids utilize a smaller more efficient internal combustion engine along with electric motors (EM) and electric generators (EG). The Ohio State EcoCAR 2 team is working on the development of next generation hybrids that are more user friendly and boast of a much more complex architecture. This allows for better fuel consumption and emissions as well as extended driving range in all-electric mode.

A transmission is an integral part of any vehicle no matter what its application is. The automotive industry started out with a manual gearbox in which the clutch inputs and gear changes were provided by the driver. This means that the driver has to physically couple and decouple the transmission from the engine drive shaft. Coupling a gear mean that the transmission and the engine are both turning at the same time, thereby "transmitting" the power developed by the engine to the wheels via the transmission.

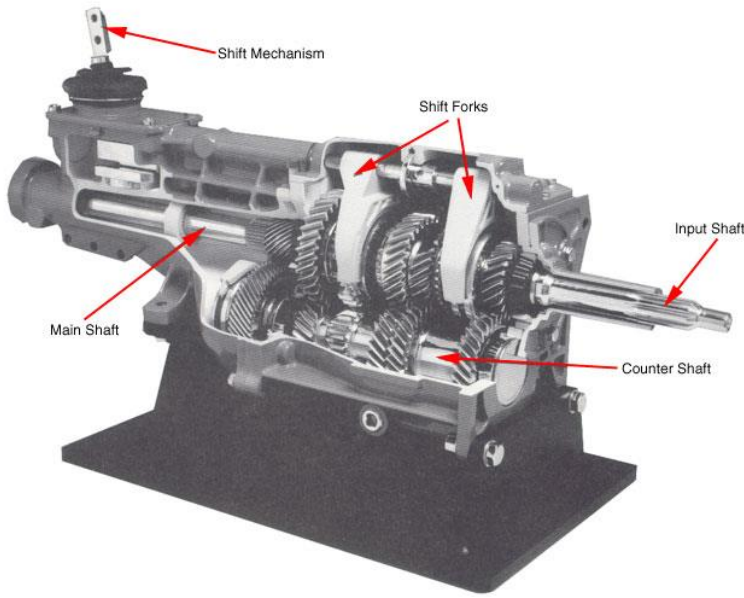

Figure 3: Internals of a Manual Transmission [2]

A manual transmission was originally completely mechanical although over time electronics have been integrated to make them more sophisticated and more number of gears have been added. Addition of more number of gears enables in having more gear ratios which thereby helps with fuel efficiency as well as with operating the engine at its optimum loading point [3].

In automatic transmissions, clutching inputs and gear changes are done by the transmission using hydraulic fluids. Automatic transmissions tend to be larger and bulkier and are usually not considered to efficient than MT's. However, over the past few years, a lot of work has been done and the latest generation of automatic transmissions are extremely efficient due to the addition of variable ratios as well as dual clutches (DCT) which makes them shift between gears at efficient points depending on certain engine parameters as well as the driver controlled throttled input. However, owing to the basic architecture of an automatic gearbox that has the bulky "torque converters" that contains the transmission fluid to allow gear changes, the addition of additional gears and clutches makes them larger.

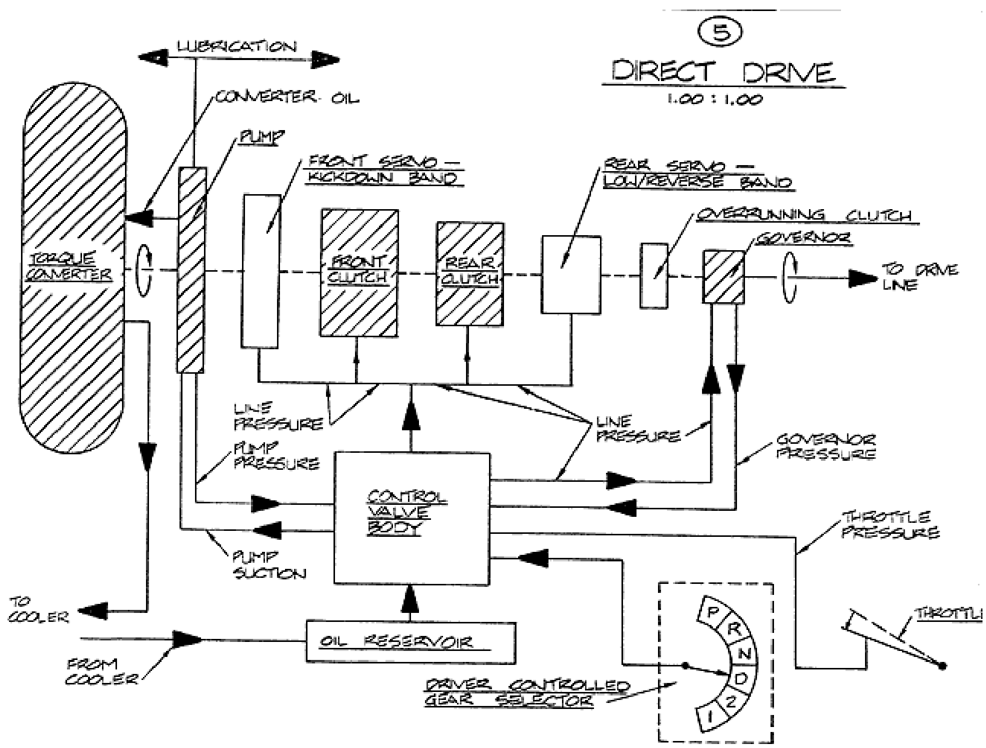

Figure 4: Internals of an Automatic Transmission [4]

The way DCT's function is that they are essentially the same transmission except with two clutches. Depending on the requirements, there are two types of DCT's. In the first type with higher power requirements, both the clutches engage and disengage at the same time thereby ensuring that all the power is transmitted. A good example is the DCT in use in the EcoCAR 1 vehicle. The second type of application has one of the clutches being used for shifting odd gears while the second clutch is used for the even gears. This is the more common application of the two types of DCT's.

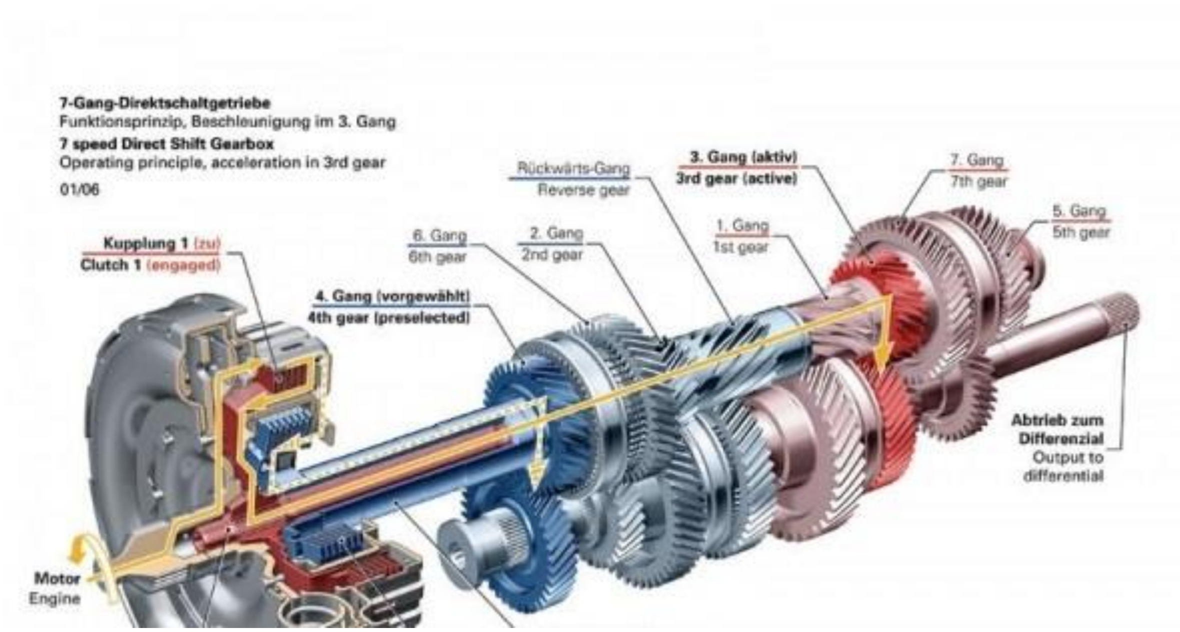

Figure 5: Internals of a Dual Clutch 7 speed Transmission (DCT) [5]

The car industry has seen an increasing number of Automated Shift Transmissions (AST). These type of transmissions allows the driver to manually change the gears. However there is no clutch input and the amount of gear changes are usually restricted due to the number of gear ratios. A good example of this type of this would be the Mercedes Benz "TipTronic" transmission. Another example would be the paddle shift gears that many performance oriented car manufacturers are tending to gravitate towards. AST's offer the driver more flexibility but essentially it is an automatic gearbox and has the same drawbacks of inefficiency and bulkiness.

Another possible idea is to use a continuously variable transmission (CVT) which has infinite gear ratios. Unlike conventional transmissions which have a fixed set of gear ratios, CVT's have 2 conical pulleys and a v-belt or chain that can move around to provide the infinite gearing ratios. The theory behind using CVT's is that no matter the throttle inputs by the driver, the CVT will adjust accordingly to ensure that the engine is operating in its most efficient region while providing smoothness and eliminating the gear hunting that is associated with conventional automatic transmissions. However, CVT's are not very good with handling a lot of torque and power through them. Another disadvantage is that the cost of the manufacturing the units is much higher than that of the conventional transmissions.

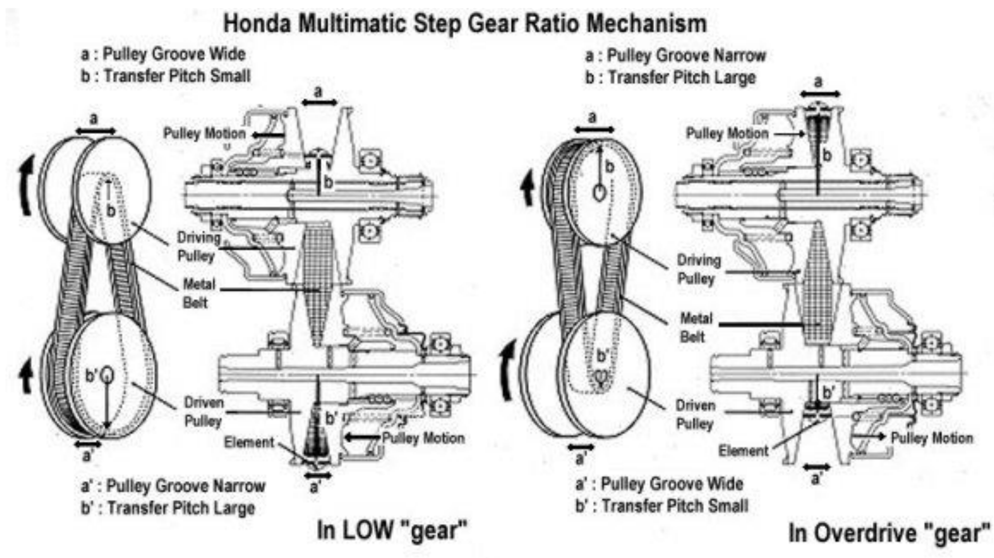

Figure 6: Internals of a Continuously Variable Transmission (CVT) [6]

This thesis deals with the development of an Automated Manual Transmission (AMT) which is essentially the complete opposite of an AST. An AMT consists of a fully functional manual transmission complete with the clutch. However, instead of having to physically use your left leg to press the clutch pedal, an electro-mechanical actuator will be used to perform the function of the human leg. The control logic behind making the transmission shift at the optimum points with minimum amount of gear shift time is carried out by a supervisory controller. The driver just needs to slide the gear shifter into drive "D" and drive it like a conventional AT while the MT's underneath does all the gear shifting. The reason behind using two of these linear actuators is to assist in shifting in different directions. Figure 1 below will help in visualizing the idea. Actuator 1 will move along the x-axis or horizontally on the shifter pattern. Actuator 2 will move along the y-axis or in the vertical direction.

Figure 6: Shift pattern of a Manual Transmission [7]

1.2 Significance of Research

The Center for Automotive Research (CAR) at The Ohio State University is where all the research is being carried out as part of the work for the EcoCAR 2 team. This type of transmission is a brand new idea and is not present on any production vehicle at the moment. The idea behind developing a radical system such as this is to combine the efficiency of a manual transmission with the ease of use and drivability of an automatic.

Figure 7: GM M32 6 speed manual transmission used for conversion into AMT [8]

Another advantage is given the tight space requirements of the vehicle due to the addition of electric motors and inverters along with a full sized ethanol E85 engine, the AMT will be easier to integrate due to its relative small size. Much work has been done over the past year in order to make this platform robust and reliable and ensure that the OSU EcoCAR 2 team wins the competition.

The first part of this thesis will deal with finding the efficiency of the linear actuators. The second part deals with finding a "black box model" of the electro-mechanical actuator that is used for the clutch. The biggest drawback of an AMT is that it cannot be used in conventional powertrains or in current generation hybrid powertrains which rely on only a single set of EM and/or EG. The way the EcoCAR 2 transmission is set up is that during a gear shift in an AMT, the front powertrain needs to be disconnected during which the rear electric motor (REM) will provide all the power. Once the supervisory controller has speed matched between the ICE and FEM (front electric motor), an ideal gear is selected and then the front electric powertrain will kick back in providing most of the power with the REM providing supplemental power. AMT's haven't been tried in commercially available hybrids but have a very great potential for extended range electric vehicles (EREV) or plug-in hybrid vehicles (PHEV). These feature series - parallel powertrain due to its efficiency and ease of use.

1.3 Project Formulation and Scope

The main deliverable of this research is to find the efficiencies of the linear actuators. It will be supplemented by the black box model of the electro-mechanical actuator as well as the performance of the linear actuator in the weather chamber.

Figure 8: SKF CAHb Linear Actuator [9]

The main motivation behind finding the efficiency is that the linear actuator has a lot of small moving parts inside that are inter-connected to each other. Hence, there is no simple method to individually characterize them as well the interaction between each of those internal parts. Finding the efficiency helps in finding the system losses and this affects the overall system efficiency of the automated manual transmission. This overall transmission efficiency is not discussed here and is out of the scope of this paper. The parameters are used in developing the model based calibration for the transmission.

The actuator efficiency tests are carried out in a manner that will closely reflect the different loads the transmission and actuator will see during a drive cycle. The tests that were carried out went beyond this and actuators were tested upto their maximum rated load limit. The efficiency was calculated using certain formulae that are applicable to a permanent magnet electric motor (PMDC) in MATLAB. The actuator behavior was studied with varying loads and input voltages. The loads varied from no load condition to 45 pounds (lbs.). The input voltage was varied from 6 volts (V) to 13V. The idea is to push the actuators to their operating boundaries and still ensure that they will perform their duty reliably.

This paper is unique in terms that it allows for gainful insight on how the actuators that are used for clutchless AMT’s vary under different conditions and its corresponding parameter values.

Chapter 2: Literature Review & Methods

The purpose of this section is to give a better understanding on the insight about automated manual transmissions (AMT) and their integration into vehicles.

2.1 AMT Development and Selection Criteria

The reason for developing an AMT was twofold. One, the EcoCAR1 vehicle utilized a single speed automatic transmission that only had an overdrive gear. The overdrive gear is considered the “final” gear of a transmission. An overdrive is the most efficient gear simply because it has a higher output than the given input. So if the input is about 1000 RPM (revolutions per minute), then the output is actually about 800 RPM depending on the gear ratios. However, overdrive has very little torque bearing capacity and this is especially important since torque is an important factor in the drivability of the car from standstill upto about 50 MPH (miles per hour).

A manual transmission was not an option because it is not allowed according to the EcoCAR2 competition rules. A conventional automatic was also not considered due to the tight space constraints.

2.2 Efficiency Comparison of Different Types of Transmissions

This section deals with comparison of efficiencies between the different types of transmissions [10]. As said before, the purpose of developing an AMT is to make the transmission very efficient and reduce driving fatigue that is associated with frequent gear shifts and clutch inputs. While MT’s are the most efficient, AT’s provide most comfort. The following tables give a comparison between the different types of transmissions that were talked about in section 1

	Time in Gear	Representative Efficiency	Current Production Efficiency Variation
Gear 1	8%	93.5%	92-96%
Gear 2	10%	92.0%	92-97%
Gear 3	21%	94.0%	93-97%
Gear 4	20%	97.4%	93-99%
Gear 5	41%	93.8%	92-97%

Table 1: Efficiency of a manual transmission [10]

	Low-Speed Ratio High-Input Torque	Mid-Speed Ratio Mid-Input Torque	High-Speed Ratio Low-Input Torque
Low-Speed	84%	86%	77%
Mid-Speed	86%	89%	80%
High-Speed	83%	85%	76%

Table 2: Efficiency of a Continuously Variable Transmission (CVT) [10]

	Time in Gear *	Efficiency	Current Production Efficiency Variation
Gear 1	9%	70.3%	60-85%
Gear 2	4%	78.1%	60-90%
Gear 3	5%	86.0%	85-95%
Gear 4	32%	86.2%	85-95%
Gear 5	40%	88.7%	83-94%

* Excludes 10% for idle

Table 3: Efficiency of a 5 speed automatic transmission [10]

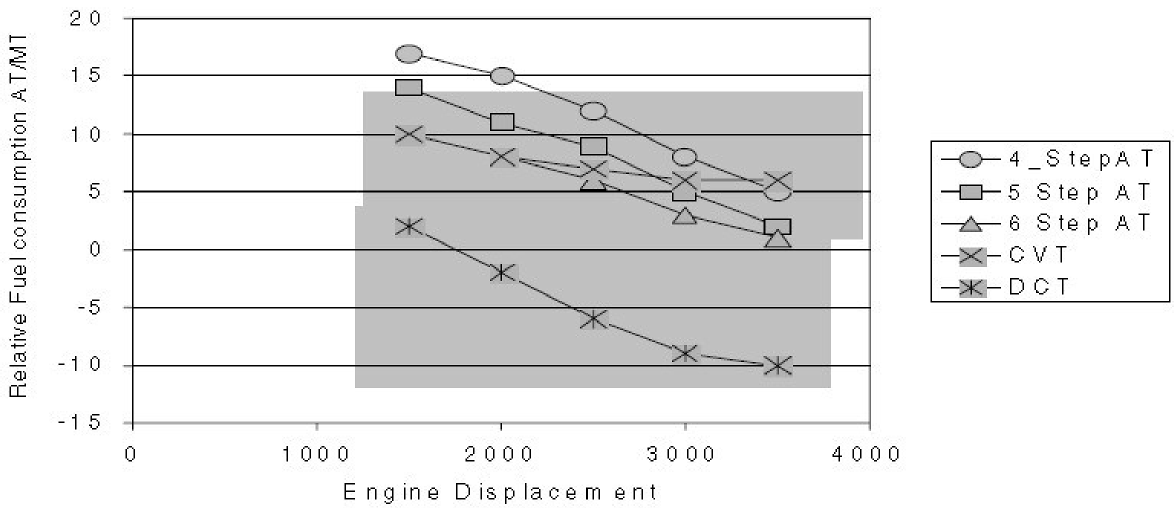

Figure 9: Fuel efficiency variation with respect to engine displacement and changing gear ratios [11]

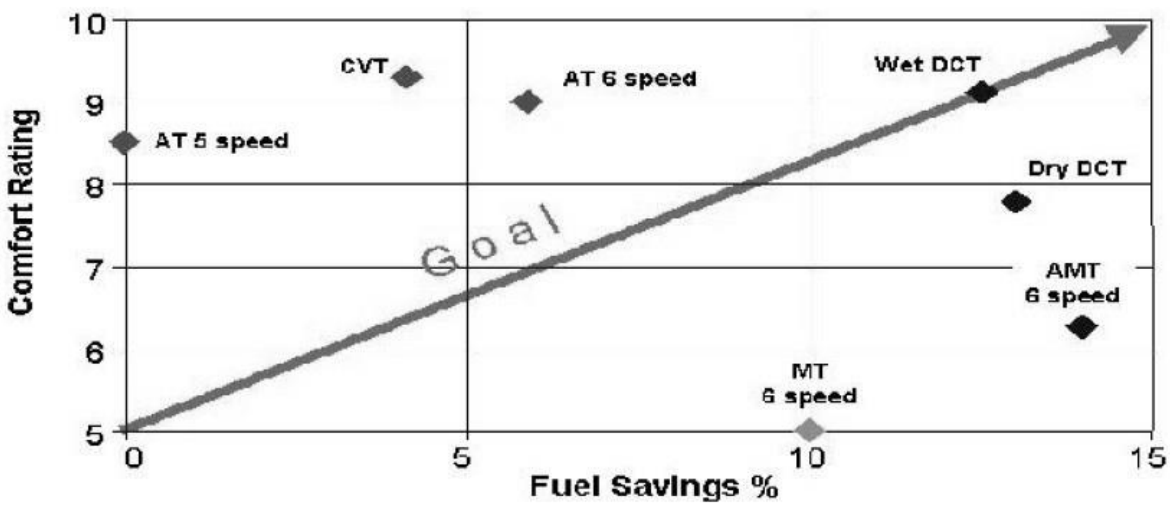

Figure 10: Fuel Efficiency variation with respect to passenger comfort rating and transmission type [11]

From the above tables, it is obvious that a manual transmission is much more efficient than an automatic transmission by about 15-25% [12]. However, a lot of people prefer to drive an automatic transmission in the American market due to its ease of operation. Hence, it is necessary to select a transmission that combines the advantages of both of these types of transmission. After comparing the different options that are out in the market, the automated manual transmission

(AMT) fits all the criteria and is hence a good path of development for the OSU EcoCAR2 vehicle. While AMT's aren't very popular in the USA car market, European car manufacturers have been using AMT's in small numbers and the numbers have been steadily on the rise since 2006[14]. Volkswagen developed an AMT for the Lupo hatchback as early as 1999 but was never a success due to reliability issues. Shift times in a manual transmission depends a lot on the driver skills as well as experience. In an AMT, the shift times are reasonably quick and vary between 0.25 and 1.5 seconds.[14]. This is sufficiently good for our application.

2.3 AMT Basics:

Based on literature review, most of the production version of AMT's seem to use a single dry clutch to provide the gear shifts. However, as stated earlier, the EcoCAR2 being an extended range plug-in hybrid, the necessity for a "clutched" shifting is not required. The supervisory controller and the front electric motor take different parameters into consideration and allow for gear shifts. This leads to the development of our AMT that has clutch less shifting [14].

Chapter 3: Experimental Set-Up

This section deals with the experimental setup as well as the test procedure that was followed in order to understand the trend of the actuator efficiency as well as get the required parameters.

3.1: Proposed Test Set Up

A DC voltage source is used that can go from 1V (volt) upto 20V. The positive and negative leads from the voltage source will power the actuator at its positive and negative leads. A breadboard will be used to account for the voltage divider rule. By definition, voltage divider rule means, “A set of two or more resistors connected in series between an applied voltages, so that the voltage at points between the resistors is a fixed fraction of the applied voltage. Voltage dividers are common in the power supplies of devices such as amplifiers, in which different subcomponents require different voltage levels for their own power supplies.”[3] This means that the output voltage can be lowered depending on the proportion of the resistors on the breadboard box. The reason for this addition is, the National Instruments (NI) Data Acquisition Box (DAQ) cannot handle any voltages greater than 5V while all the test voltage values range from 6V to 13V.

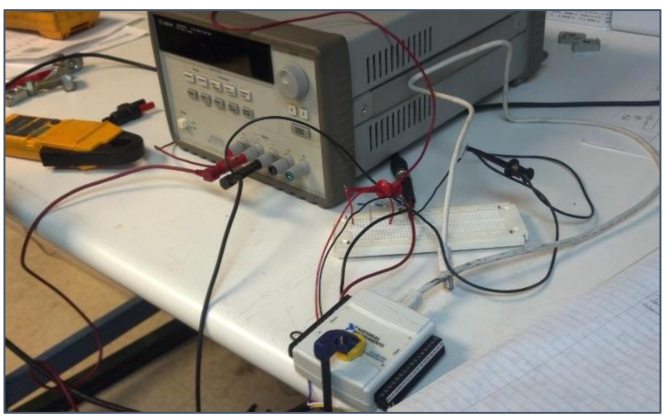

Figure 11: Test Set Up

Number of Units	Apparatus
1	Fluke Current clamp
1	NI DAQ 6009
1	Agilent DC power supply
1	Actuator frame
1	Linear actuator
1	Load bucket

Table 3: Linear Actuator Apparatus

The arrangement in this case was to use a 1K ohm and 2K ohm resistors which means that the recorded output voltage is actually 1/3rd of the actual value. A zener diode was also added in parallel to the resistors. The actuators have a tendency to show a big spike in current and corresponding voltage levels just when they have started moving. This is an inherent characteristic of a permanent magnet direct current motor (PMDC). The linear actuators use the PMDC to provide the motion. More will be discussed about the internal mechanism of the actuator in a later section. This voltage spike causes the DAQ to involuntarily shut off as a safety feature. A zener diode allows current flow only in one way and hence needs to be positioned in the correct direction. It is usually placed in the opposite direction of the current flow in the circuit. A zener diode permits prevent current flow until a certain amount of current level is reached. Once that level is attained, the zener diode permits the flow of electric current in the circuit only in one direction. Next a current clamp is used to measure this output voltage from the potentiometer in the electric actuator. A current clamp actually measures voltage and is then converted to current using a clamp specific factor. For these tests, the current clamp used was rated at 1V = 100 mA (milli-amps).

The linear actuators supplied by SKF are powered by a potentiometer that reads supplied voltage from the supply to the PMDC. The PMDC is then connected to a set of gear which in turn connect to a rack and pinion in order to convert the rotational motion to linear motion. This in turn connects to the lead screw that allows for the actuator tip to extend and retract. The lead screw moves along a track that has sensors along the end limits in order to stop drawing power and to prevent possible damage to the actuator unit.

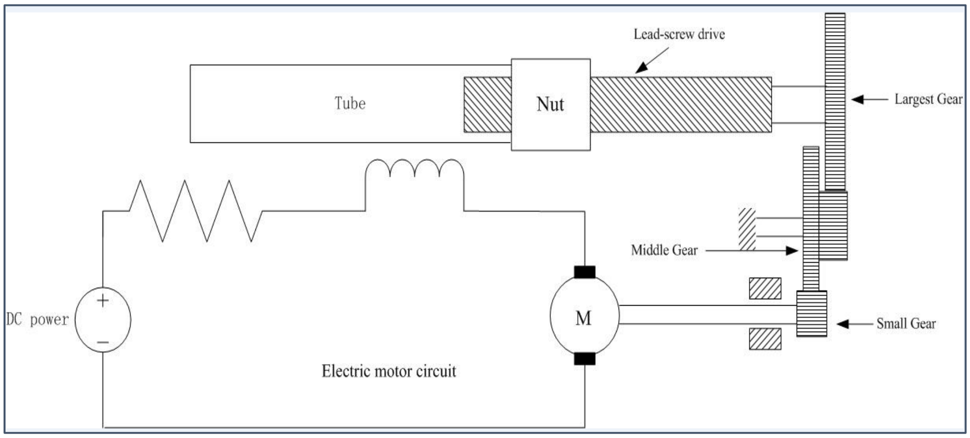

Figure 12: Internals of the linear actuator

The equation for finding the gear ratios is:

$$Gearing\ Ratio = \frac{n1}{n21} * \frac{n22}{n3} = \frac{18}{47} * \frac{23}{45} = 0.1957$$

Where:

n1 = number of teeth on first gear

n21 = number of gear on second gear – larger side

n22 = number of gear on second gear – smaller side

n3 = number of gear on third gear

The lead screw of the actuator has 42.5 grooves and is 5.139 in long.

$$Lead = \frac{Length}{No. of\ grooves} = \frac{5.139}{42.5} = 0.1209\ in/lead$$

The inch to millimeter (mm) conversion is given by -

1in = 25.4mm

Therefore, the lead is 0.1209 in/lead or 3.07 mm/lead.

The conversion factor from angular velocity of the motor end to the linear velocity of the actuator end is given by - 3.07*0.1957 = 0.6009 mm/rev.

1 revolution (rev) = 6.28318531 radians

Therefore, the conversion factor is 0.6009 mm/rev or 0.0956mm/rad.

3.2: Electro-mechanical Actuator

The electro mechanical actuator is manufactured by FTE Automotive and will be used as the clutch actuator. This actuator has a brushless DC motor that drives a recirculating ball spindle which in turn displaces a hydraulic piston to create pressure and the resulting movement due to the fluid displacement and accompanied volume change. The inner view of the electro mechanical actuator can be clearly seen in figure 13. Figure 14 shows the schematic on how the clutch actuator will be connected to the 12V electric system of the car. The biggest advantage of using the electro mechanical actuator is that it is fast and controllable. The maximum pressure rating is 200 bar which is sufficient for our application. Another advantage is that the characteristic force to imitate the foot force to being used to move the clutch pedal can be infinitely varied and selected within the specified operating range. Having this sort of an actuator couples to the linear actuators to provide the gear shifts ensures that there is no need for a third pedal or bulky torque converter, thereby freeing up valuable space for necessary components required for the complex hybrid architecture of the OSU EcoCAR2 team. . Much has not been done regarding the clutch actuator in terms of testing due to time constraints and hence the outputs of the FTE actuator could not be analyzed completely. Using the limited data available and the very quick response of the time outputs, a black model will be created.

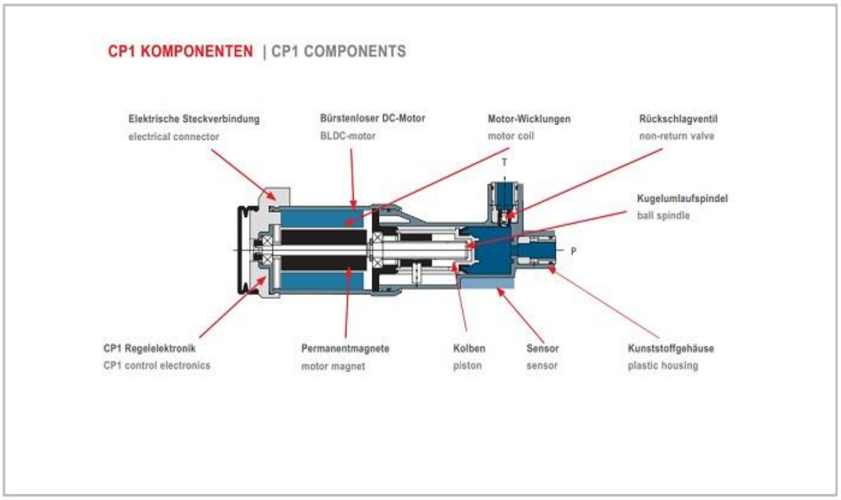

Figure 13: Internals of the electro-mechanical FTE actuator [13]

Another issues is that the inputs of the clutch actuator was not recorded while testing and hence the "ident" function in matlab cannot be used in order to identify the system model. More of this is discussed in section related to the clutch actuator.

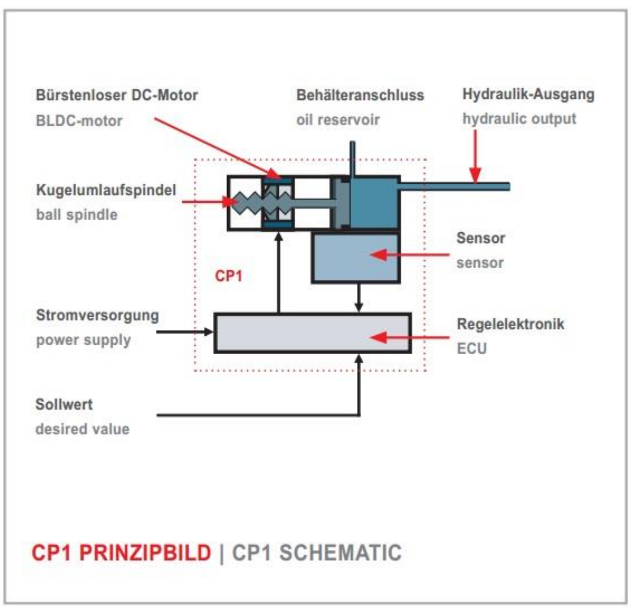

Figure 14: Input-output correlation of the FTE actuator [13]

3.3: Test Stands

The test stands being used for testing the linear actuators went through multiple revisions. The reason being the first few stands needed to be completely dismantled for testing the actuators in different directions. Another reason for changing the design was to prevent the wires that were used to suspend the load bearing bucket from rubbing against the metal frame. This contact between the wire and the frame resulted in additional friction and caused the overall actuator efficiency to reduce significantly by about 11%. The final design of the stand included changes that not only incorporated all the requirements listed above but also allowed the actuators with the frame and mechanical shift cables to be housed in the weather chamber to study shifting characteristics and stability of the whole system in extreme climate conditions.

3.4: Equations Used for Setup

The following are the equations to find the parameters of the PMDC and are used for testing as well as developing the PMDC Simulink model:

$$\frac{di_a(t)}{dt} = \frac{e_a(t)}{L_a} - \frac{(R_a * I_a)}{L_a} - \frac{e_b(t)}{L_a} \qquad [1]$$

$$T_m(t) = K_i * i_a(t) \qquad [2]$$

$$e_b(t) = K_b * \frac{d\theta_m(\mathrm{t})}{\mathrm{dt}} = K_b * \omega_m(\mathrm{t}) \qquad [3]$$

$$\frac{d^2\theta_m(t)}{dt^2} = \frac{T_m(t)}{J_m} - \frac{T_L(t)}{J_m} - B_m * \frac{d\theta_m(\mathrm{t})}{J_m} * \frac{1}{dt} \qquad [4]$$

Symbols used:
T_m (t) = motor torque
i_a (t) = armature current
T_L (t) = load torque
K_b (t) = back – emf constant
θ_m (t) = rotor displacement
ϕ = magnetic flux in air gap
R_a = armature resistance
ω_m (t) = rotor angular velocity
L_a = armature inductance
J_m = rotor inertia

e_b (t) = back emf
B_m = viscous-friction coefficient

It is important to note that all the calculations are done in the steady state region. This has two primary benefits:

1. Helps in ensuring the values are calculated in almost identical conditions for each case where the load and/or voltage is varied.
2. Eliminates the use of differential terms in the above equations and thereby helps in making calculations easier and reduces the chances of errors.

These equations need to be set up in a way so that they can use the outputs from the DAQ directly and calculate the required values in a logical manner. The resistance and inductance of the armature of the coil of the DC motor are known values and were measured using an LCR meter.

3.5: Derivation of Equations:

This section deals with the relation between the equations of sections 3.1 and 3.2.

Equation 1 can be written as:

$$\frac{di_a(t)}{dt} = \frac{e_a(t)}{L_a} - \frac{(R_a * I_a)}{L_a} - \frac{e_b(t)}{L_a}$$

OR

$$\frac{L_a * di_a(t)}{dt} = e_a(t) - (R_a * I_a) - e_b(t)$$

OR

$$e_b(t) = e_a(t) - (R_a * I_a) - \frac{L_a * di_a(t)}{dt}$$

OR

Eb5_filt = V5s - La*C5s_di_filt - R5*C5s_filt

This is equation 13.

$$T_m(t) = K_i * i_a(t) \qquad [2]$$

Equation 2 is the same as equation 23. Equation 23 also includes the acceleration constant value to make the value of the torque as accurate as possible. However, the value of the acceleration constant is very small compared to the rest of the values and can hence be neglected.

$$e_b(t) = K_b * \frac{d\theta_m(\mathrm{t})}{\mathrm{dt}} = K_b * \omega_m(\mathrm{t}) \qquad [3]$$

Equation 3 can also be written as:

$$K_b = \frac{e_b(t)}{\omega_m(\mathrm{t})}$$

OR

Kb5_filt=Eb5_filt./W5_filt

Hence equations 3 and 21 are the same.

Finally considering equation 4 –

$$\frac{d^2\theta_m(t)}{dt^2} = \frac{T_m(t)}{J_m} - \frac{T_L(t)}{J_m} - B_m * \frac{d\theta_m(\mathrm{t})}{J_m} * \frac{1}{dt}$$

In the steady state region, all differential values become zero. Hence the equation reduces to:

$$T_m(t) = T_L(t) \qquad [4]$$

Hence the torque value found in equation 23 is a lumped equivalent of T_m and T_L.

An excel sheet comprising of all the calculated values for each case of extension and retraction can be found in the appendix.

3.6 Methodology of Experiment

This section deals with how the equations that are provided in the previous equation are used and the logic behind how the Matlab code flows. The data that is recorded by the DAQ is stored as a large array of numbers in notepad. These then need to be converted to an excel sheet which in turn then needs to be converted into a usable format for Matlab. This is done by using the "xlsread" command in Matlab. This converts the excel sheet into a .mat file which is a recognized format. However, before converting the excel sheet, the voltage and current data in the raw output need to be zeroed out and filtered so that most of the signal disturbances are removed, thereby making later data calculations easier.

Depending on how the wires were connected from the linear actuator to the DAQ, there are three different columns – one each for the voltage, output current and position. The voltage and current values used are relative to the position of the actuator tip and hence the first step is to find the minimum and maximum positions of the actuator for each test. This is done by using the following codes:

```
S5smax=max(data(:,5));                [5]
S5smin=min(data(:,5));                [6]
```

Here, "S5s" is the position of the actuator tip. The "max" and "min" commands help in finding the maximum and minimum values respectively. The data(:,5) is calling the data in all rows in the 5th column. These data points are the position values for this test set-up.

The next step is to find the corresponding current and voltage values. This is done by the following codes:

```
C5s=data(:,2).*10               [7]
V5s=(data(:,8))*3               [8]
```

Equation 7 has a multiplication factor of 10. This is to account for the conversion factor of the current clamp. The clamp used for this experiment was rated at 1 Ampere (A) = 100 milli-volts (mV). Equation 8 has a multiplication factor of 3. This is to account for the voltage divider rule that is used in the bread board in the circuit. More of this has been explained in section 2.2.

Next we find the corresponding time dependence of each of these parameters by:

```
T5s=data(:,1)               [9]
```

After these are done, a digital filter is created for all the data and then the "current" data is further filtered.

```
[N D] = butter(4,.01);                [10]
C5s_filt=filtfilt(N, D, C5s);         [11]
```

The armature inductance (L_a) and resistance (R5) values were found to be 514.2e-6 Henry (H) and 0.875 ohms respectively using a LCR meter.

The value of this filtered current can be found using:

```
C5s_di_filt=central_diff(C5s_filt,T5s)              [12]
```

The C5s_filt term refers to the values referred to within each experiment in the steady state. The central difference theorem is used in order to find the timed derivatives of all the filtered current values.

The back emf (e_b) is calculated next by the following equation:

```
Eb5_filt=V5s-La*C5s_di_filt-R5*C5s_filt              [13]
```

Once the back emf voltage is found, it is used to calculate the linear speed of the actuator. This is done by differentiating the recorded position of the actuator with respect to time using the central difference theorem.

```
speed5=central_diff(S5s,T5s)                              [14]
```

After this, the resultant value is filtered and a mean value is found.

```
speed5_filt=filtfilt(N, D, speed5)                        [15]
speed5_mean=mean(speed5_filt(1000:3000))                  [16]
```

Equation 16 has the number (1000:3000) – this is the steady state region for this particular iteration and changes for each test. The steady state region can be found by selecting the current plot and zooming into the required region.

Acceleration is the differential of speed or the double differential of position. Using the linear speed calculated above, the acceleration is found by the following:

```
Ac5=central_diff(speed5,T5s)                               [17]
Ac5_filt=filtfilt(N, D, Ac5)                               [18]
```

Equation 18 is used to remove the disturbances from the recorded data and get the required filtered value. Next the angular velocity of the motor is found. This is related to the measured linear velocity of the actuator. The relation between the angular speed and the linear speed can be found in section 2.2

```
W5_filt=speed5_filt/0.095642                                [19]
Meanfilt_W5=mean(W5_filt(1000:3000))                        [20]
```

The penultimate step is to find the back emf constant (K_b) from the below equations:

```
Kb5_filt=Eb5_filt./W5_filt                                  [21]
Kb5_filt_mean=mean(Kb5_filt(1000:3000))                     [22]
```

Finally, the last step is to find the torque generated by the actuator.

```
T5=Kb5_filt.*C5s_filt+A*Ac5_filt                            [23]
T5_mean=mean(T5(1000:3000))                                 [24]
```

3.7: Calculating Actuator Efficiency

As stated at the beginning of this paper, the idea behind calculating the efficiency of the actuators is to estimate the internal losses within the different parts of the actuator. The values that are found using the equations above will be used to calculate the efficiency of the actuators and thereby find the internal losses.

In general:

$$Percentage\ Efficiency = \frac{output}{input} * 100\% \qquad [26]$$

In case of the actuators, the electrical power accounts for the input and the mechanical work done accounts for the output. The output is given by the product of angular speed and linear speed and is given by:

```
out=w*(1)*(speed5_mean)*(0.001)                                      [27]
```

where,

out = mechanical output
w = weight (N)
speed5_mean = linear speed (mm/s)

The conversion factor of 0.001 is to convert the linear speed from mm/s to m/s.

The loads that are placed in the bucket are in pounds (lbs)' to simulate the weights of the different gears. To convert these to Newtons (N) – the weight in pounds needs to be multiplied by 0.453592*9.81. This converts the pounds into kilograms (kg) and then into Newtons.

The input is given by:

```
in=(T5_mean-0.0127-1.41758e-5*Meanfilt_W5)*Meanfilt_W5                    [28]
```

Where:

In = input power
T5_mean = torque (N.m)
Meanfilt_W5 = angular velocity (rad/s)
0.0127 = coefficient of static friction
1.41758e-5 = inertial moment of DC motor

Thus, the efficiency calculation is given by:

```
E=(out/in)*100                                                              [29]
```

3.8: Evaluation Criterion

A data set is generally considered good if the recordings are consistent with the range of expected values. The two major guiding factors to determine whether the recordings are good or not are:

1. For a constant voltage supply and increasing load input, the current drawn by the motor will be higher. This will also result in a corresponding increase in torque requirements. However, the linear and angular speeds will drop and the efficiency will also drop by a small amount.
2. For same load and increasing input voltage, the current requirement increases but at a

much smaller rate. The linear and angular speeds also rises with increasing input voltage and steady load.

3. Since K_b (back emf constant) is a constant value, every test should give a K_b value that is within close approximation of one another.
4. All the data is recorded into an “extension” and “retraction” set. The “retraction” set of data is more predictable as it is easier to record the values with minimal human interface. The “extension” data is trickier since it involves having to manually hold the actuator in place while it is extending. This involves having to use a wrench and electrical wires to hold the setup rigidly. This is done in order to replicate the testing conditions for each test as closely as possible to one another. The actuator needs to be flipped around for each type of test. This is because the potentiometer inside the actuator records values more accurately when it is doing work against gravity. Hence, sufficient care needs to be taken that the electrical wires do not rub anywhere against the frame and the wrench is also held firmly in place.

Chapter 4: Experimental Evaluation

4.1 Initial Testing Data

The actuators were tested to find the starting and stalling current values. 6V, 9V and 12V which are listed in table 3.1.2. For these, the experiments were carried out in the same manner as described in chapter 3. The data was then imported into Matlab and 3 plots were made for each of the above voltages – actuator position, voltage and current with respect to time. The starting and stopping times were recorded manually while using LabView to data acquisition. When the plots are made, the corresponding current values were read at those times. The three plots for the recorded currents are listed below.

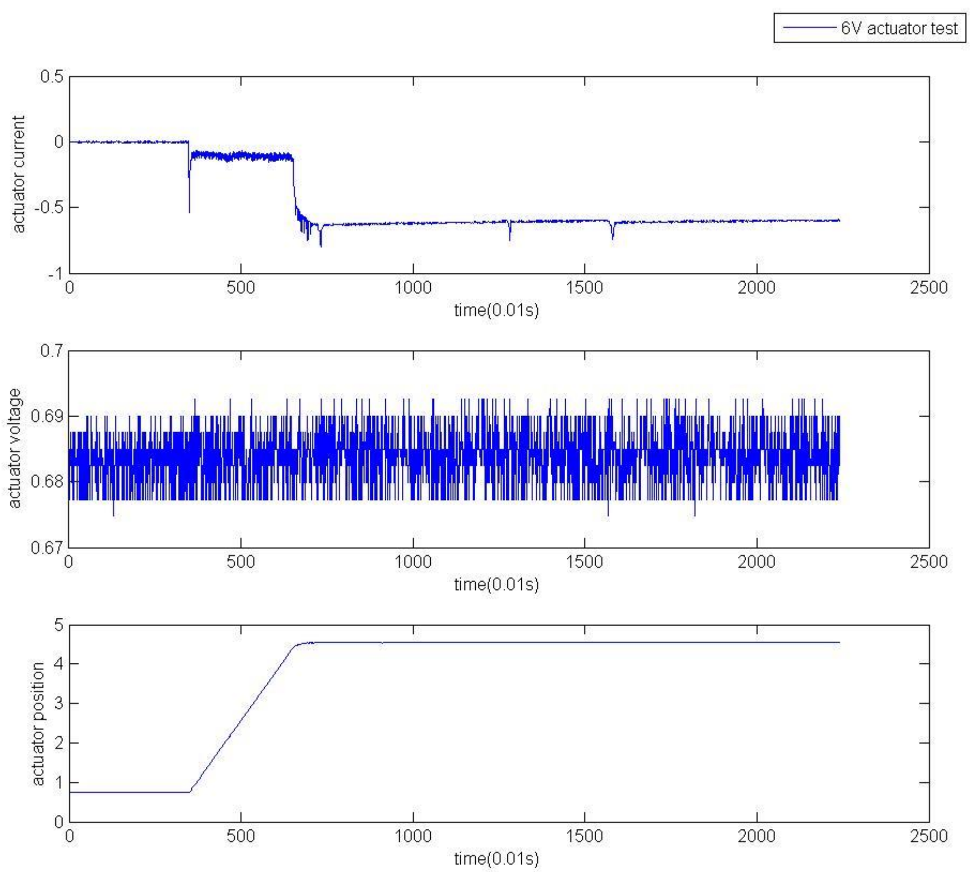

Figure 15: Starting and Stalling Current at 6V

In the 12V graph, there is a drop in the voltage value from about 10s to 14s. This is a very small fall – about 0.3Amperes (A), and does not affect the speed or the reliability of the actuations in any way. This is due to the steady state currents being smaller than the current required to start spinning the PMDC.

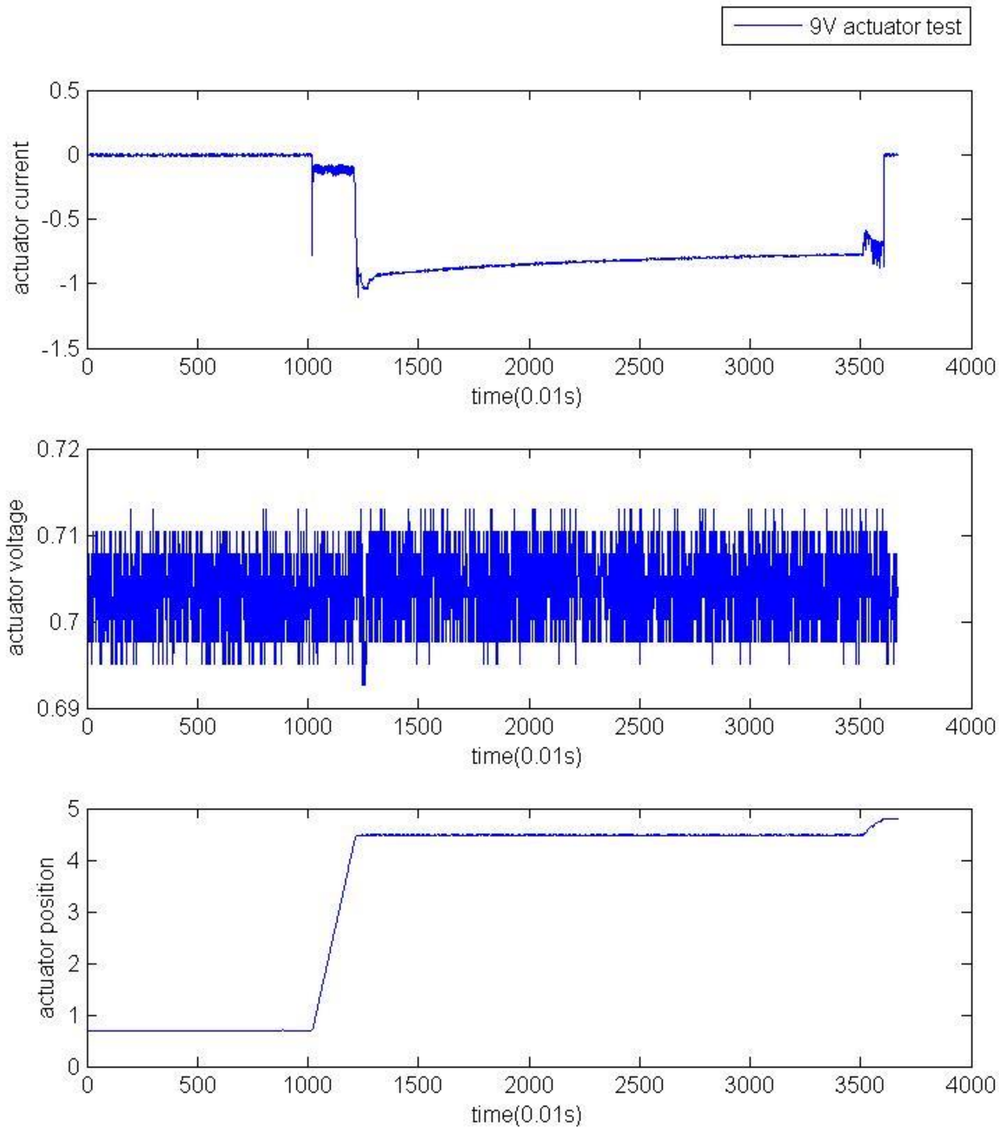

Figure 16: Starting and Stalling Current at 9V

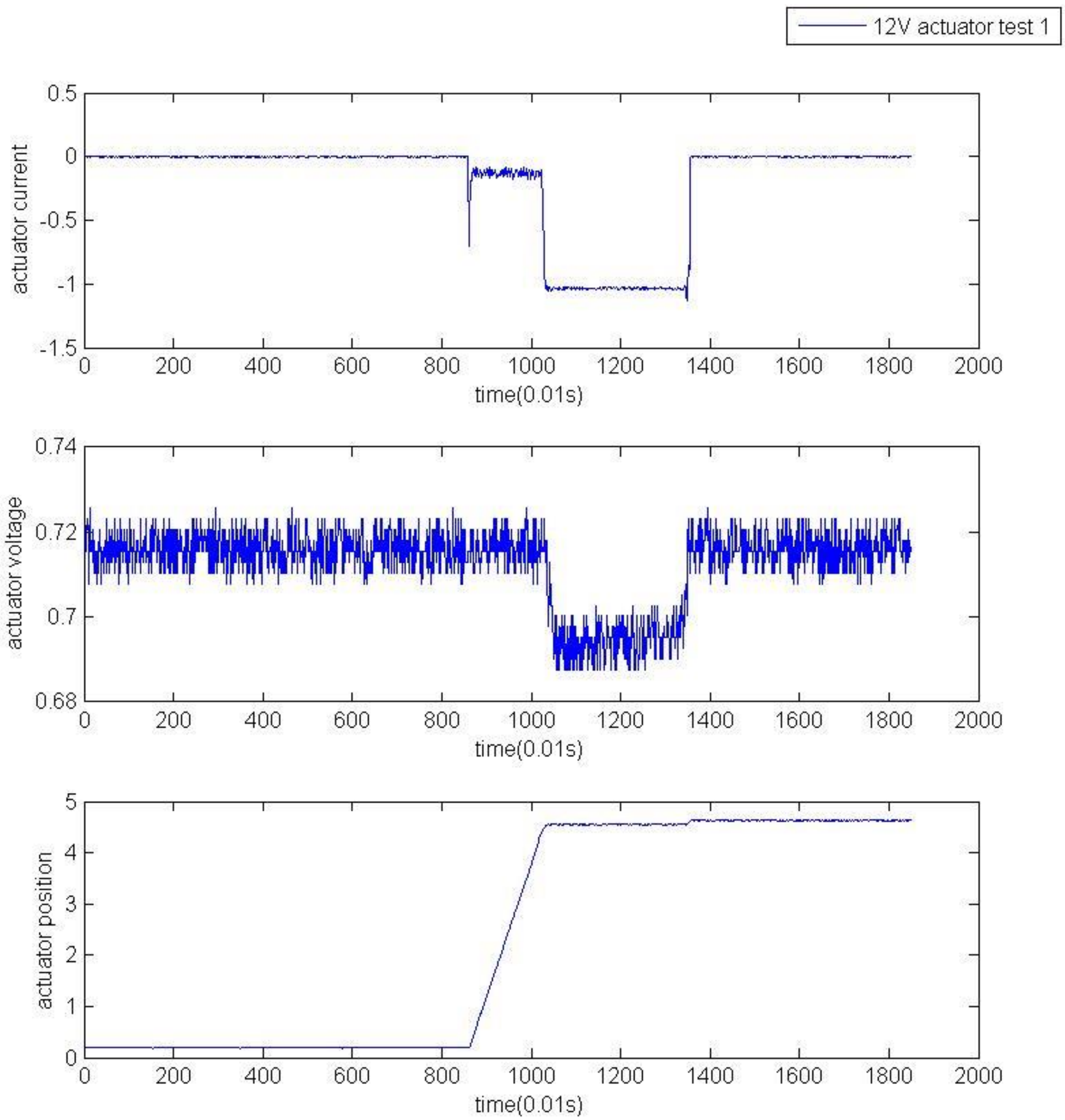

Figure 17: Starting and Stalling Current at 12V

4.2: Test Set-Up

A variety of experimental test set ups were tried in the evaluation of this design.

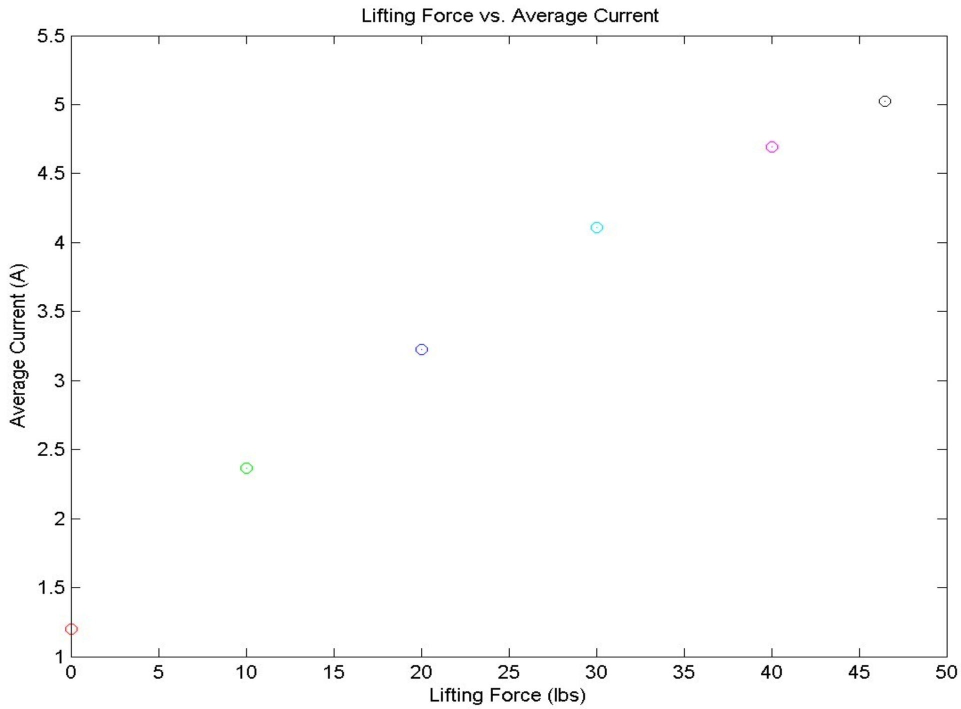

Figure 18: Initial Lifting Force vs. Current drawn

Before, the actuator parameters could be found it was necessary to make sure that actuators were indeed linear and that they would perform accordingly. This was done by varying loads from 0lbs to 26.5lbs while the voltage was being held constant at 7V. This results in varying levels of current requirements as shown in figure 18. These current values are plotted in the figure below and as can be seen, the data is linear. The linear actuators are rated upto a 100 N (about 22.5lbs). The purpose behind testing the actuator a little over the rating is to actually determine if any non-linearities are introduced. Each set of data is measured twice to rule out any uncertainties in measurements. On a side note, the actuator was tested with 100lbs and 10-13V, it still managed to perform its functions although in a rather sluggish and non-linear manner.

4.3: Actuator Test Results

The linear actuator had to be tested four different times to meet the testing criteria. This is because in the first test set, both sets of data a given load and voltage combination were recorded right after each other within the same expansion movement of the actuator. In other words, the actuator was connected and allowed to run for 2 seconds, then removed from the circuit, then brought back another 2 seconds to run it for the second time for 2 seconds. All of this was done with one expansion stroke. Although the rough data that was collected seemed to follow the predicted linear trend, problems arose when trying to pick the steady state regions to calculate the required parameters as well as for filtering the data into usable numbers.

This was due to the fact that both the steady state regions for a given stroke of the actuator were very close to one another and each steady state region was only about 2 seconds which is not a large enough range for Matlab to compute the values. The presence of two spikes for each time the DC motor started also further compounded the problems.

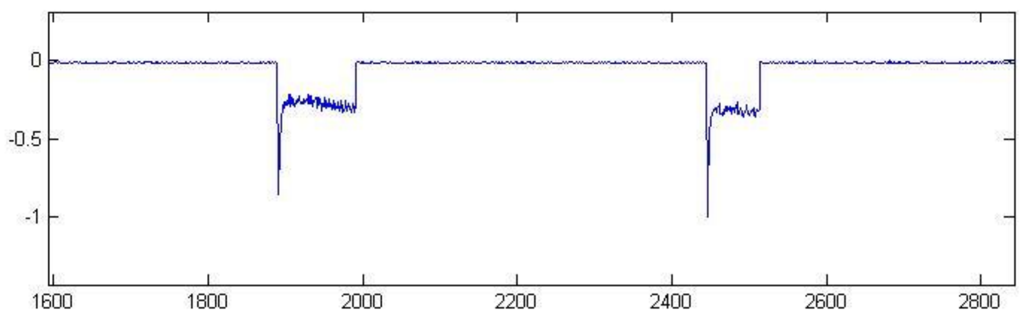

Figure 19: Testing results – first iteration

The experiments carried out in the above two sets only included testing the actuator facing down and "retracting" the load up. Learning from the errors and issues of the above two experimental sets, the third set was carried out. This time after all the "retraction" tests were carried out, the frame was rebuilt in order to accommodate the actuator facing up while still being able to lift the loads. These would be the "extension" tests where the actuator is facing up and pushing up the loaded bucket up to its extended position. Although the data for the “retraction” set were mostly fine, the values for the “extension” experiments followed no reasonable trend, especially the efficiency values which are directly linked to the torque values.

It was found that these bad values were due to the electrical wire rubbing against frame. When the bucket was being carried up by the actuator, the electrical wire would become extremely taut due to the tension and straighten out. This caused the space between the wire and the frame that is present in retracted state to diminish, causing contact between two and significant friction. Although this might not seem much, the effect of frame to wire contact caused the efficiency value to reduce by a significant amount as much as 11-15%.

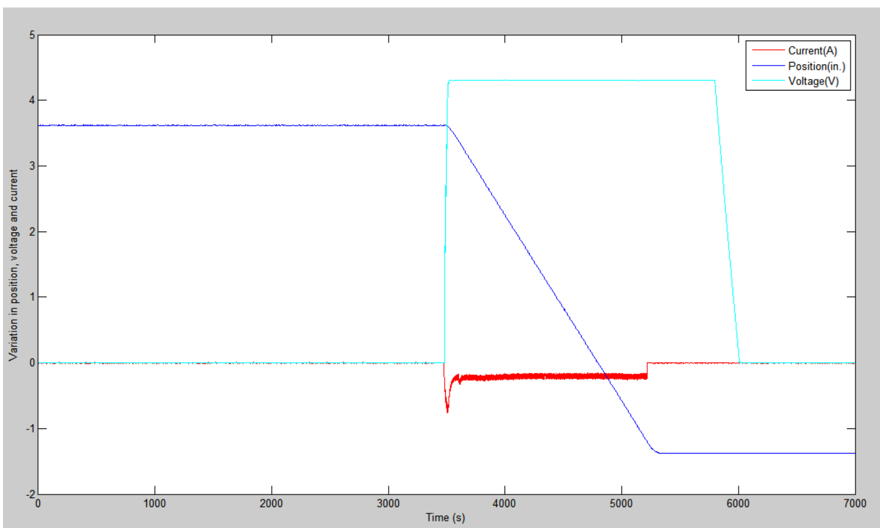

Figure 20: Final test raw data

In figure 20, the red line is the current drawn to move the actuator with the light blue line being the voltage drawn from the power supply. The dark blue line is representative of the change is position of the actuator end. The steady state region in the current line is picked individually for each test and then used for all the calculations. Appendix A1 shows all the parameters of the actuator tabulated in an excel sheet for the extension tests. Based on the readings, it was found the actuators provided robust performance that continually met the required expectations and trend lines even after numerous cycles. It can be seen that the linear speeds and corresponding angular speeds increase with increasing voltage input for holding a constant load. Conversely, the speeds reduced for increasing load and constant voltage. The back emf constant (K_b) was also extremely steady at around 0.0190. The corresponding current levels varied depending on the voltage inputs and load levels. The current trend varies as follows: the value increases for constant voltage and increasing loads. It also increases for increasing voltage and constant voltage. The values range from about 0.93A for 6V and 0 lbs to about 2.76A for 13V and 40lbs. The corresponding torque generated varied from 0.017N/m for 6V and 0lbs to 0.053 N/m for 13V and 40lbs. The efficiency values were extremely close to what is expected out of a PMDC motor and to those recorded using the PMDC Simulink model. It varies from 37% to 55% for all the cases. However, the values that are generated in low load cases i.e loads of 6.25 lbs and below are not very accurate and the data varies by as much as 20%. This variation is due to the minor change in internal resistance of the entire system which depends on the amount of load and voltage levels being supplied Minor discrepancies might also have crept into the data due the inability to hold the actuator perfect perpendicular to ground at its fully extended position and at the higher loads.

Appendix A2 shows the tabulated results for the extension data. This data set is very accurate and can be seen in figure 24. Once again, the pattern in data change is exactly similar to that explained in the above paragraph. The angular speed varied from about 206 rad/s for 6V and 26.875lbs to about 663 rad/s for 13V and 0lbs case. The current drawn varied from about 0.85A for 6V and 0lbs to 2.86A for 13V and 26.875 lbs. Corresponding torque levels were 0.015N/m and 0.05N/m respectively. The efficiency was within a much narrower range for the extension cases and varied from about 23% to 34% respectively for the stated inputs.

The PMDC motor also has some built in error in the form of backlash. This means that potentiometer does not record accurately when rotational direction is reversed for the first few revolutions. The backlash value was measured to be 1.5revolutions. It is only after 1.5 revolutions that play is overcome and values are recorded accurately.

Finally the FTE clutch actuator was also tested. However, meaningful data could not be extracted due to the extremely fast response time and its inability to record the variation of input signal (position) and the corresponding output signal (pressure). Figure 20 shows the response output of the FTE actuator.

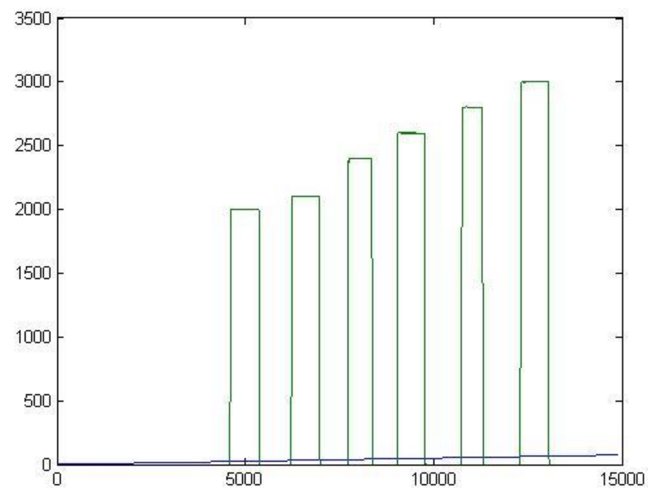

Figure 21: FTE actuator test output – position vs. current drawn

As can be seen the spikes show the response time for changing position. The original plan of action was to use “ident” in Matlab that accounts for the inputs and outputs of the system and gives the corresponding transfer function. However, due to the extremely quick response time and the inability to record the input using ident was not possible. The reaction time was calculated for each spike and averaged out to be 0.0013s which is extremely small and very hard to record.

The PMDC motor was also modeled using Simulink in order to better understand its characteristics and its behavior as well as to validate the experimental data. Figure 21 displays the Simulink model.

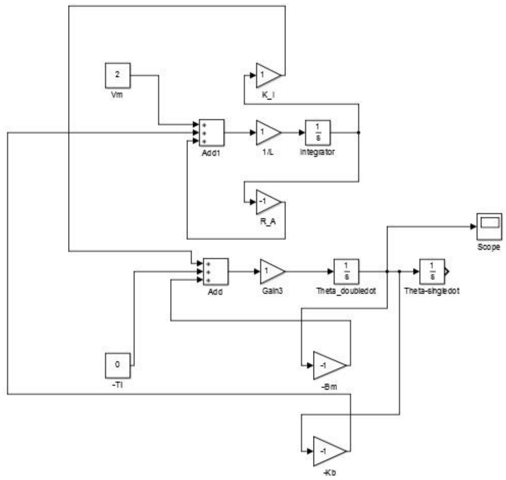

Figure 22: Linear Actuator PMDC Simulink model

4.4: Results Validation

Parameter name	Value
Electric motor inductance (L_a)	514.4e-06 H
Electric motor resistance (R_a)	0.88397 ohm
Back-emf constant(K_b)	0.0190
Torque constant (K_t)	0.0190
System equivalent inertia (J_m)	1.111e-5$\mathrm{kg.m^2}$
System equivalent viscous coefficient (B_m)	1.2867e-5 N.m/rad
System efficiency	21%
Linear actuator efficiency	38%
System coulomb friction	0.0240 N.m

Table 4: Linear Actuator Parameters

Utilizing the values from the table 4 and the Simulink block diagram shown in figure 22, the angular speed of the actuator was collected and compared to the test data. The results are extremely close to each other and can be seen in the following figure.

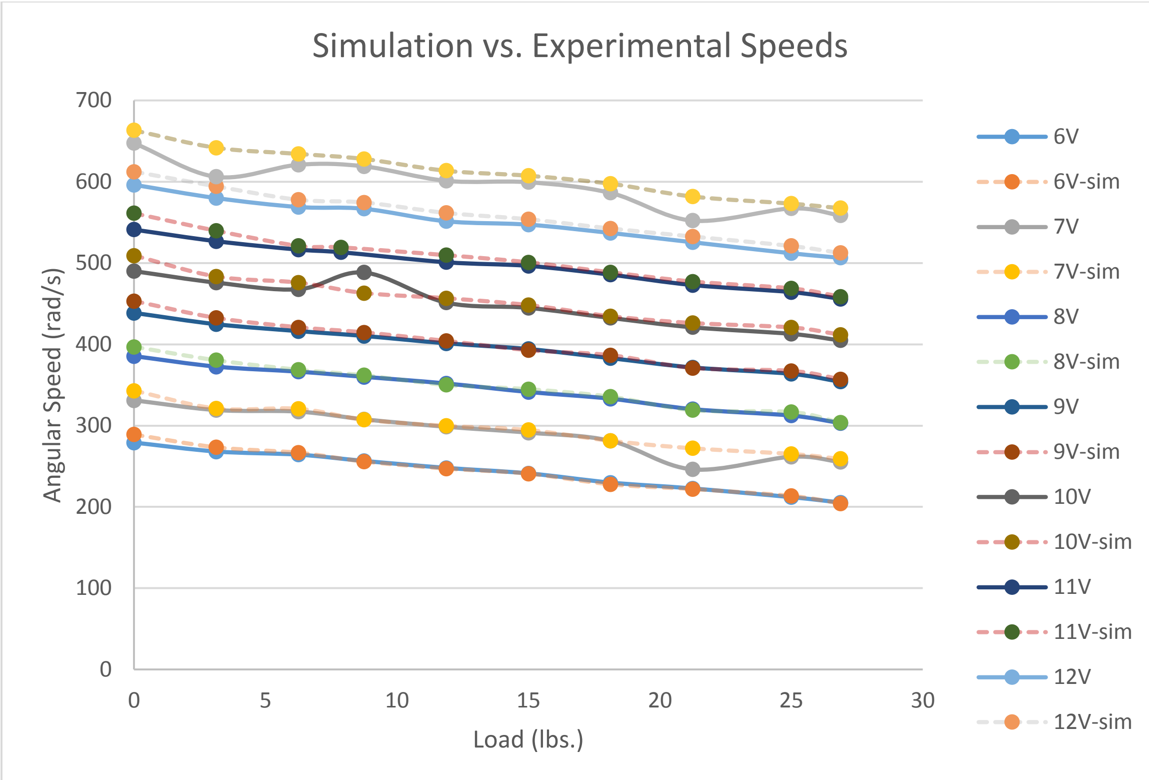

Figure 23: Testing vs. simulation results

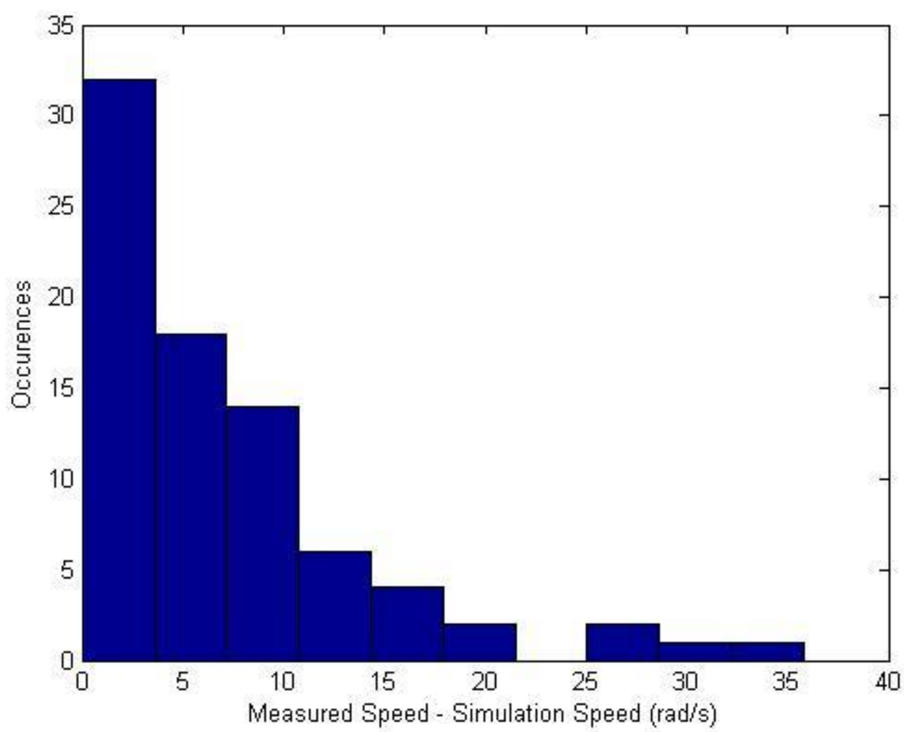

Figure 24: Theoretical vs. Experimental Data Error

Chapter 5: Conclusion

5.1: Conclusions

The testing of the actuators has provided great insight as to how the different components work and how the overall system behavior varies under differing operating environments. This data has helped in the writing of the control strategy for the AMT that has successfully run and competed against other vehicles in the same class, rather successfully. The goal was to calculate the parameters and characterize the trend pattern of the speed, torque, current and back emf constant as well as the efficiency. The most important learning from this project is that behavior of the permanent magnet DC (PMDC) motors is understood which is useful not only in terms of its use within the scope of designing an AMT but also for other applications where PMDC motors are being used. Given the time frame and the resources available, the data is accurate and difference between the simulation and experimental results are within close proximity of each other. The efficiency of the actuators averages to about 37.92% and to about 21% with the actuators connected to the transmission linkages. These values are similar to those predicted and proved to be useful in the writing of the control code. As part of the analysis, the mean absolute error, the room mean square error and the standard deviation of the errors were calculates. These came to 7.1 rad/s, 9.86 rad/s and 6.88 rad/s respectively. These values once again validate the experimental results and give strong backing that the PMDC model is accurate.

5.2: Sources of Error

The fact that the experimental data is so close to the simulation results validates the PMDC motor Simulink model. However there are a few data outliers within the experimental data set. These are apparent in the extension data set and this is due to having to hold the extending part of the actuator with a wrench in order to hold it straight and prevent any sort of buckling or bending.

Another source of error could be possibly from the 18 gauge wire that was used to connect the load bucket to the actuators. These tend to rub against the metal frame under extreme operating points despite taking sufficient care to try and avoid this from happening. These are the two most important factors that can cause disturbance in the data.

5.3: Scope of Future Work

The most important work that can be done is to develop a test stand that will allow for testing the clutch actuator in a proper manner and record meaningful data that can be analyzed to understand the behavior over its operating region. Another possibility to could be to look into using faster linear actuators. This will help in reducing the shift time between gears which is currently at about 0.9 seconds which is still a bit slower than a regular manual transmission (MT). Finally, this system in its current state depends on having two sets of electric motors to accomplish the gear shifts without interrupting power delivery. A possibility could be to modify the system such that it can be used in cheaper hybrids that feature only a single electric motor. Finally it is important to characterize the non-linearities and irregularities in the actuators at very low load and low voltage operating points.

Chapter 6: References

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Chapter 7: Appendices

Appendix A1: Retraction Data

Voltage (V)	Weight(lbs.)	Steady State Range	Linear Speed (mm/s)	Angular Speed (rad/s)	Kb	Current (A)	Torque (N/m)	Efficiency
6	0	2500-5000	26.0014	271.8618	0.0189	0.9318	0.0176	
6	3.125	3000-5000	25.4318	265.9064	0.0189	1.0574	0.02	78.0794
6	6.25	2000-4000	25.1494	262.954	0.0188	1.1523	0.0216	78.5266
6	8.75	3000-5000	24.5259	256.4348	0.0187	1.3272	0.0248	58.1228
6	11.875	2000-4000	23.7024	247.824	0.0188	1.4755	0.0277	48.592
6	15	1000-4000	23.0308	240.8025	0.0186	1.6714	0.0311	50.1792
6	18.125	2000-4000	22.1275	231.8282	0.0186	1.8579	0.0346	45.4478
6	21.25	2000-4000	21.2864	222.5628	0.0186	2.0594	0.0384	45.3472
6	25	2000-4000	20.1451	210.6298	0.0187	2.2869	0.0428	43.5274
6	26.875	2000-4000	19.5364	204.2657	0.0184	2.5004	0.046	40.1594
7	0	3000-4000	30.796	321.9923	0.0189	0.9742	0.0184	
7	3.125	3000-4000	30.1707	315.4547	0.0191	1.0546	0.0201	78.0794
7	6.25	2000-4000	30.1855	315.6094	0.0188	1.1477	0.0216	83.2258
7	8.75	1000-3000	29.3068	306.4219	0.0188	1.3366	0.0252	56.0906
7	11.875	1000-3000	28.4375	297.3324	0.0188	1.5412	0.029	48.592
7	15	2000-3000	27.2734	287.2529	0.0187	1.8014	0.0336	42.5687
7	18.125	2000-4000	27.0042	282.3462	0.0187	1.9037	0.0356	45.4478
7	21.25	2000-4000	21.0712	220.3131	0.0187	2.0906	0.0391	43.7989
7	25	2000-4000	24.7769	259.0585	0.0187	2.3897	0.0447	40.7249

7	26.875	2000-4000	24.1699	252.7124	0.0188	2.5034	0.0471	40.1594
8	0	3000-4000	36.027	376.6858	0.0188	0.9828	0.0185	
8	3.125	3000-4000	35.2485	368.5459	0.019	1.0655	0.0202	79.4547
8	6.25	2000-3000	34.8266	364.1355	0.0189	1.197	0.0266	66.3794
8	8.75	1000-2000	34.1174	356.7196	0.019	2.615	0.0251	58.0503
8	11.875	2000-3000	33.5431	350.7148	0.0187	1.5551	0.0291	48.6129
8	15	1000-2000	32.3291	338.0217	0.0189	1.7632	0.0333	43.8644
8	18.125	1500-3000	31.7656	332.1598	0.0187	1.9523	0.0366	43.2856
8	21.25	1500-3000	30.5967	319.9084	0.0189	2.1493	0.0407	41.3166
8	25	1500-3000	29.426	307.668	0.0189	2.408	0.0456	39.6557
8	26.875	1500-3000	28.6678	299.7402	0.0189	2.5939	0.049	37.8455
9	0	4000-5000	41.1757	430.5192	0.0189	0.8996	0.017	
9	3.125	3000-4000	40.1297	419.5828	0.019	1.1086	0.021	60.7054
9	6.25	2000-3000	39.4862	412.8542	0.019	1.2394	0.0235	56.6624
9	8.75	1500-3000	38.9086	406.8147	0.019	1.3856	0.0263	50.4403
9	11.875	1500-3000	38.1332	398.7077	0.0189	1.6061	0.0303	44.5209
9	15	1500-2500	37.2083	389.0367	0.0189	1.787	0.0338	42.9133
9	18.125	2500-3500	36.3936	380.5193	0.0189	1.9817	0.0375	41.6605
9	21.25	1500-3000	35.4214	370.3543	0.0189	2.2095	0.0417	39.7141
9	25	1500-2500	34.1478	357.0376	0.019	2.4654	0.0467	38.7278
9	26.875	1500-2500	33.6263	351.5852	0.0189	2.6108	0.0493	37.6398

10	0	2500-3500	45.6362	477.1566	0.019	0.9617	0.0183	
10	3.125	2500-3500	44.8841	469.2923	0.019	1.1391	0.0217	51.489
10	6.25	1500-2500	44.1871	462.0049	0.019	1.2846	0.0245	49.4679
10	8.75	1500-2500	43.7766	457.7128	0.0189	1.4298	0.0271	46.6685
10	11.875	1500-2500	42.6493	445.9266	0.019	1.6472	0.0313	41.5279
10	15	1000-2000	41.9016	438.1083	0.019	1.8202	0.0346	41.2648
10	18.125	2000-3000	41.1707	430.4669	0.0189	2.0321	0.0384	39.9728
10	21.25	1500-2500	39.9926	418.1494	0.019	2.2532	0.0428	38.1824
10	25	2000-3000	38.887	406.5888	0.019	2.5205	0.0478	37.0752
10	26.875	2000-3000	38.1216	398.5865	0.019	2.6937	0.0511	35.7705
11	0	2500-3500	50.4699	527.6959	0.0191	0.9706	0.0185	
11	3.125	2000-3000	49.55	518.0782	0.0192	1.1319	0.0217	53.6206
11	6.25	2000-3000	48.8131	510.3733	0.0191	1.3367	0.0255	42.8726
11	8.75	1500-2500	48.5502	507.6237	0.019	1.445	0.0275	45.4239
11	11.875	1000-2000	47.5468	497.1333	0.019	1.6919	0.0321	39.5907
11	15	1500-2500	46.8389	489.732	0.0189	1.8832	0.0356	39.1442
11	18.125	1500-2500	46.163	482.6646	0.0189	2.0677	0.039	39.1648
11	21.25	1500-2500	44.6865	467.2268	0.019	2.3048	0.0439	36.8009
11	25	1500-2500	43.643	456.3165	0.0189	2.6032	0.0492	35.5134
11	26.875	1500-2500	43.0399	450.0103	0.019	2.6923	0.0512	35.8431
12	0	2500-3400	55.8588	584.0405	0.0189	1.0133	0.0192	
12	3.125	2500-3000	54.4859	569.6855	0.0191	1.1449	0.0219	52.3177

12	6.25	2500-3000	53.733	561.8135	0.0191	1.3477	0.0257	42.5093
12	8.75	1000-2000	53.3976	558.3065	0.019	1.4998	0.0285	41.4828
12	11.875	2000-2500	52.2886	546.7118	0.019	1.7147	0.0326	38.4854
12	15	1000-2000	51.5145	538.6176	0.019	1.9302	0.0366	37.3247
12	18.125	1500-2500	50.658	529.6622	0.019	2.1259	0.0403	37.0486
12	21.25	1500-2500	49.7636	520.3113	0.0189	2.3477	0.0444	36.2637
12	25	1500-2500	48.1902	503.8603	0.0189	2.7072	0.0512	33.5268
12	26.875	1000-2000	46.7232	498.9771	0.019	2.7512	0.0523	34.7662
13	0	2000-3000	60.489	632.4519	0.019	0.9914	0.0189	
13	3.125	2500-3000	59.5336	622.4631	0.0191	1.1742	0.0224	47.5711
13	6.25	2000-3000	58.5371	612.0435	0.0191	1.3971	0.0267	38.2569
13	8.75	1500-2500	58.2552	609.0969	0.019	1.5454	0.0293	38.7396
13	11.875	1500-2500	56.7112	592.9532	0.019	1.8488	0.0352	32.8166
13	15	1500-2500	56.4517	590.2399	0.0189	1.96	0.0371	36.5641
13	18.125	1500-2500	55.2013	577.1662	0.0189	2.2496	0.0426	33.7157
13	21.25	1000-2000	49.6768	519.4033	0.019	2.3096	0.0439	36.9339
13	25	1500-2500	53.2269	556.522	0.019	2.6793	0.0508	34.1524
13	26.875	1500-2000	52.321	547.0501	0.0192	2.7565	0.0528	34.4223

Appendix A2: Extension Data

Voltage (V)	Weight (lbs.)	Steady State Range	Linear Speed (mm/s)	Angular Speed (rad/s)	Kb	Current (A)	Torque (N/m)	Efficiency
6	0	3000-5000	-27.3835	-286.3125	-0.0182	0.8527	-0.0155	N/A
6	3.125	2000-4000	-25.8545	-270.3256	-0.0182	1.1952	-0.0217	23.935
6	6.25	2500-4000	-25.3917	-265.4867	-0.0182	1.2996	-0.0236	34.394
6	8.75	2000-5000	-24.5384	-256.5646	-0.0183	1.4332	-0.0262	35.5
6	11.875	2500-4000	-23.7261	-248.0722	-0.0181	1.6781	-0.0304	34.416
6	15	3500-6000	-23.1061	-241.5898	-0.0182	1.7857	-0.0324	37.814
6	18.125	2000-4000	-21.7907	-227.836	-0.0181	2.0946	-0.0379	34.373
6	21.25	2000-4000	-21.2908	-222.6096	-0.018	2.2322	-0.0401	36.516
6	25	3000-5000	-20.3866	-213.1554	-0.0181	2.3932	-0.0433	37.961
6	26.875	2000-4000	-19.7422	-206.4176	-0.0179	2.5794	-0.0462	36.881
7	0	2500-4500	-32.541	-340.2373	-0.0182	0.8847	-0.0161	N/A
7	3.125	2000-3800	-30.8706	-322.7723	-0.0181	1.2532	-0.0227	22.343
7	6.25	2500-4000	-30.4916	-318.8102	-0.0181	13,340	-0.0242	34.266
7	8.75	2500-4500	-29.5509	-308.9739	-0.0183	1.4599	-0.0268	35.563
7	11.875	2500-4000	-28.6695	-299.7588	-0.0182	1.7226	-0.0313	33.598
7	15	2000-4000	-28.2504	-295.3764	-0.0182	1.8008	-0.0327	38.439
7	18.125	1000-2500	-26.797	-280.1804	-0.0136	-1.175	0.016	-15.6
7	21.25	2000-4000	-25.9992	-271.8387	-0.0181	2.3131	-0.0419	34.798
7	25	2500-4500	-25.2624	-264.1348	-0.0182	2.4363	-0.0444	37.251
7	26.875	2000-3500	-24.6582	-257.8173	-0.018	2.6352	-0.0474	36.094

8	0	2800-4000	-37.6789	-393.9577	-0.0182	0.8886	-0.0162	N/A
8	3.125	1500-3000	-35.9925	-376.3255	-0.0182	1.268	-0.023	23.307
8	6.25	2000-3000	-35.2281	-368.3326	-0.0182	1.4118	-0.0257	30.66
8	8.75	2000-4000	-34.7228	-363.0502	-0.0183	1.4768	-0.027	36.692
8	11.875	2000-3500	-33.3719	-352.6889	-0.0182	1.7557	-0.0319	33.52
8	15	1500-3000	-32.9586	-344.6038	-0.0183	1.8574	-0.034	36.832
8	18.125	1500-3000	-31.9391	-333.9439	-0.0182	2.1417	-0.0389	34.555
8	21.25	2000-4000	-30.6522	-320.4888	-0.0182	2.4022	-0.0438	33.135
8	25	1500-3000	-30.3189	-317.0039	-0.0182	2.4669	-0.0449	37.231
8	26.875	2000-4000	-29.3122	-306.4788	-0.0182	2.715	-0.0493	34.658
9	0	2500-4000	-42.7232	-446.6988	-0.0181	0.957	-0.0174	N/A
9	3.125	1500-2500	-41.1072	-429.8028	-0.0182	1.2891	-0.0234	23.965
9	6.25	1500-2500	-40.1324	-419.6109	-0.0182	1.4694	-0.0268	25.476
9	8.75	2500-3500	-39.5721	-413.7525	-0.0183	1.5347	-0.0281	34.822
9	11.875	2000-3000	-38.6185	-403.7813	-0.0182	1.8086	-0.0329	32.478
9	15	1500-3000	-38.1975	-399.3805	-0.0181	1.9225	-0.0349	36.245
9	18.125	2500-4000	-36.8693	-385.4929	-0.0182	2.1956	-0.04	33.841
9	21.25	2000-3500	-35.6533	-372.7785	-0.0182	2.4585	-0.0448	32.209
9	25	2500-3500	-35.4255	-370.3965	-0.0182	2.5068	-0.0456	37.161
9	26.875	2000-3500	-34.09	-356.4333	-0.0183	2.7688	-0.0506	33.894
10	0	2500-4000	-48.0949	-502.8641	-0.0098	0.9432	-0.0093	N/A

10	3.125	2000-3000	-46.1606	-482.639	-0.0182	1.3358	-0.0243	23.037
10	6.25	2000-3000	-45.2886	-473.5223	-0.0182	1.5046	-0.0274	29.034
10	8.75	2000-3000	-49.6351	-518.9672	-0.0183	1.6173	-0.0296	33.827
10	11.875	2000-3500	-43.7019	-456.9323	-0.0182	1.8663	-0.0339	31.753
10	15	3000-4000	-43.2094	-451.7823	-0.0182	1.9513	-0.0355	36.189
10	18.125	1500-2800	-41.5751	-434.6951	-0.0183	2.2808	-0.0416	31.472
10	21.25	1500-2500	-40.5534	-424.0123	-0.0183	2.4901	-0.0455	32.4
10	25	2500-3500	-40.1185	-419.4656	-0.0183	2.5607	-0.0469	36.203
10	26.875	1500-3000	-39.3457	-411.3854	-0.0182	2.7716	-0.0506	34.532
11	0	2500-3600	-53.0549	-554.7235	-0.0181	1.0109	-0.0183	N/A
11	3.125	1000-2000	-51.2402	-535.75	-0.0182	1.3537	-0.0246	23.813
11	6.25	2300-3100	-49.9937	-522.7166	-0.0183	1.5585	-0.0285	27.371
11	7.876	2000-3000	-49.6351	-518.9672	-0.0183	1.6173	-0.0296	33.827
11	11.875	2200-3100	-48.2756	-504.7529	-0.0182	1.9644	-0.0358	29.245
11	15	2000-3000	-48.1332	-503.2641	-0.0182	2.0066	-0.0365	35.26
11	18.125	2000-3300	-46.7311	-488.604	-0.0183	2.2939	-0.0419	32.733
11	21.25	2000-2800	-45.7562	-478.4115	-0.0183	2.5011	-0.0457	32.906
11	25	2000-3000	-45.1362	-471.9285	-0.0183	2.5919	-0.0475	36.148
11	26.875	2500-3500	-44.1538	-461.6575	-0.0183	2.8288	-0.0518	33.861
12	0	3000-4000	-58.1826	-608.3376	-0.0113	1.0422	-0.0117	N/A
12	3.125	500-1500	-56.4395	-590.1117	-0.0181	1.393	-0.0253	23.606
12	6.25	800-1800	-55.0931	-576.0342	-0.0182	1.6241	-0.0296	26.089

12	8.75	2500-3500	-55.0128	-575.1946	-0.0179	1.6316	-0.0297	35.329
12	11.875	1500-2500	-53.1877	-556.1121	-0.0183	2.02	-0.0369	28.466
12	15	3500-4500	-53.1704	-555.932	-0.0182	2.0222	-0.0369	35.466
12	18.125	1400-2200	-52.077	-544.4991	-0.0182	2.3138	-0.042	33.324
12	21.25	2000-3000	-50.7851	-530.9916	-0.0183	2.5371	-0.0463	32.794
12	25	1000-2000	-49.7747	-520.4267	-0.0183	2.7275	-0.0499	34.009
12	26.875	3300-4300	-49.1707	-514.1124	-0.0183	2.86	-0.0524	33.826
13	0	2600-3600	-63.3704	-662.5794	-0.018	1.0944	-0.0197	N/A
13	3.125	1800-2700	-56.4055	-589.7562	-0.0182	1.3832	-0.0251	24.135
13	6.25	1500-2400	-60.2497	-629.9504	-0.0182	1.6641	-0.0303	25.88
13	8.75	1500-2500	-60.1609	-629.0215	-0.0182	1.6581	-0.0302	35.739
13	11.875	1100-2000	-58.2947	-609.509	-0.0182	2.057	-0.0375	28.379
13	15	2000-3000	-58.228	-608.8124	-0.0182	2.048	-0.0374	35.809
13	18.125	1900-2900	-56.9719	-595.6787	-0.0182	2.3391	-0.0427	33.229
13	21.25	2000-3000	-55.9725	-585.2289	-0.0182	2.5562	-0.0466	33.143
13	25	2000-3000	-55.2779	-577.9666	-0.0183	2.6764	-0.0489	35.846
13	26.875	2000-3000	-54.5669	-570.5327	-0.0183	2.8661	-0.0518	34.979

Appendix A3: Miscellaneous Data

Input voltage(V), load(lbs)	Measured Current (A)
8V, 10lbs	2.157
10V, 10lbs	NaN
12V, 10lbs	2.615
14V, 10lbs	2.335
8V, 20lbs	NaN
10V, 20lbs	2.946
12V, 20lbs	3.252
14V, 20lbs	3.481
8V, 30lbs	3.710
10V, 30lbs	NaN
12V, 30lbs	4.703
14V, 30lbs	3.914
8V, 40lbs	4.448
10V, 40lbs	4.550
12V, 40lbs	5.212
14V, 40lbs	4.550
8V, 46.5lbs	4.627
10V, 46.5lbs	4.830
12V, 46.5lbs	5.110
14V, 46.5lbs	5.518

Table 5: Supplied voltage vs. Current drawn

Input Voltage (V)	Starting Current Value (A)	Stalling Current Value (A)
6	5.416	6.296
9	7.86	**9.994**
12	10.407	10.332

Table 6: Starting and stalling current of actuator

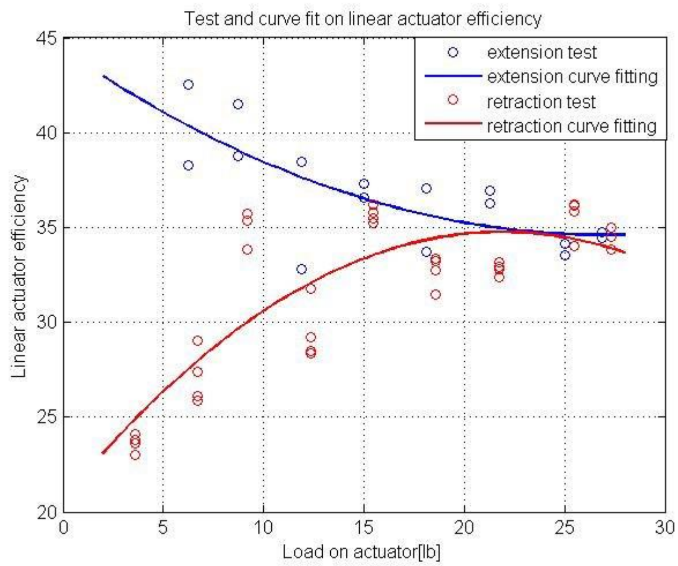

Figure 25: Curve fitting - efficiency of linear actuator

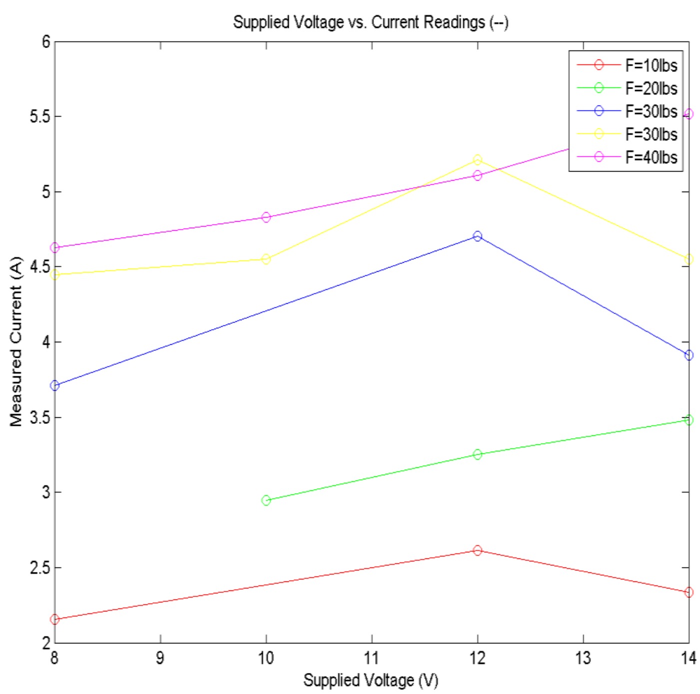

Figure 26: Supplied voltage vs. current reading

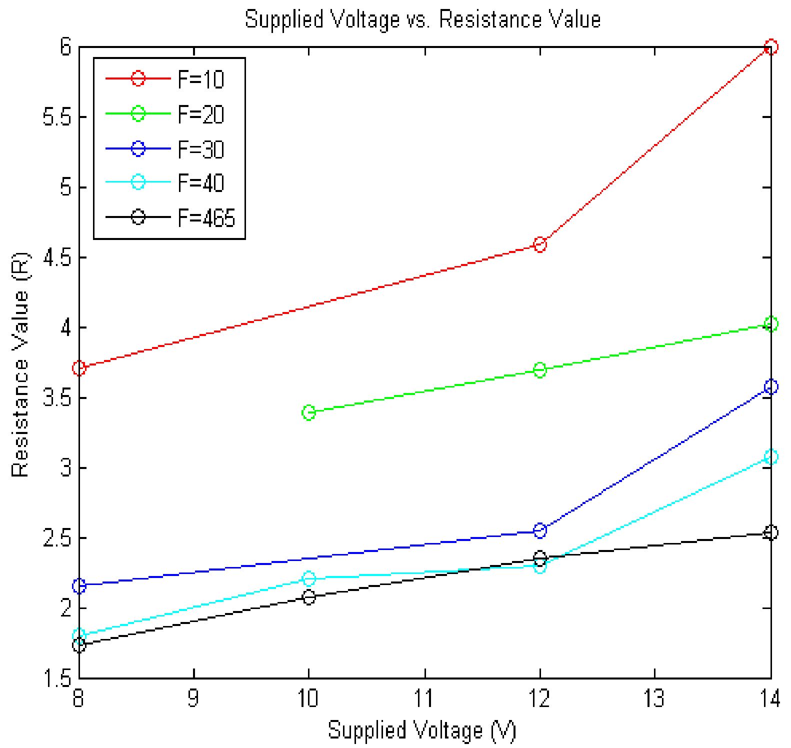

Figure 27: Supplied voltage vs. resistance values

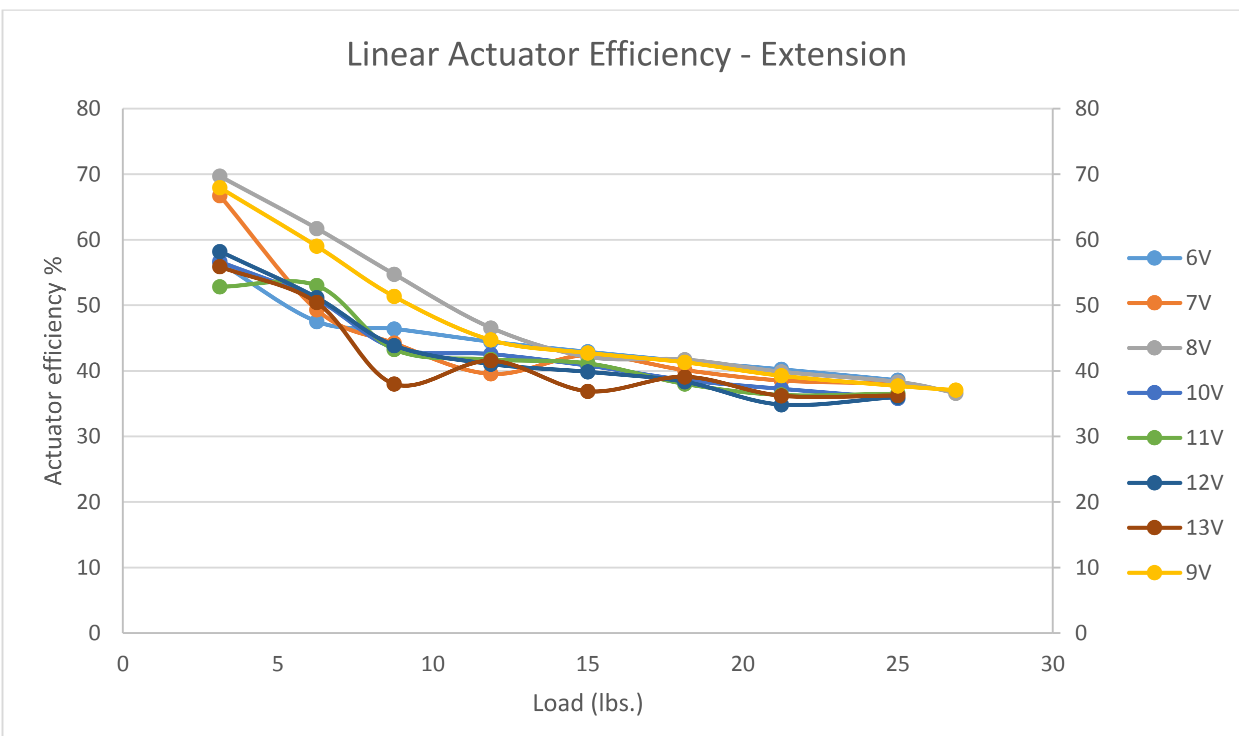

Figure 28: Actuator Efficiency - Extension

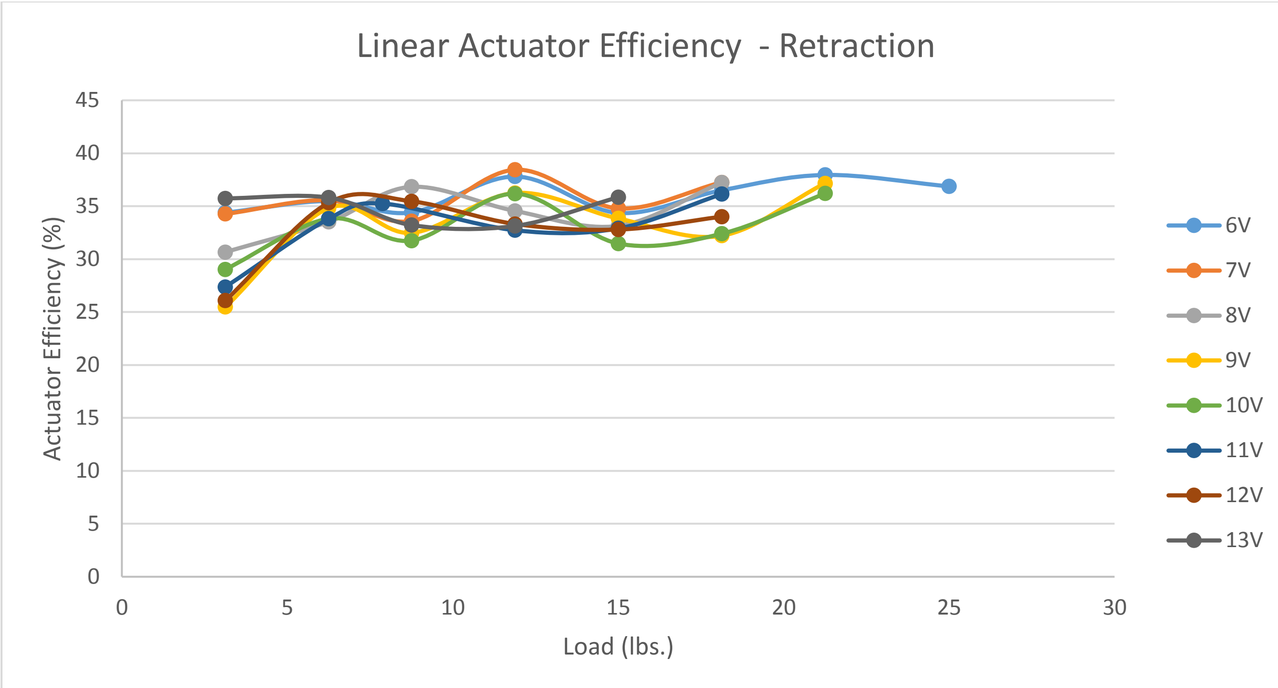

Figure 29: Actuator Efficiency - Retraction